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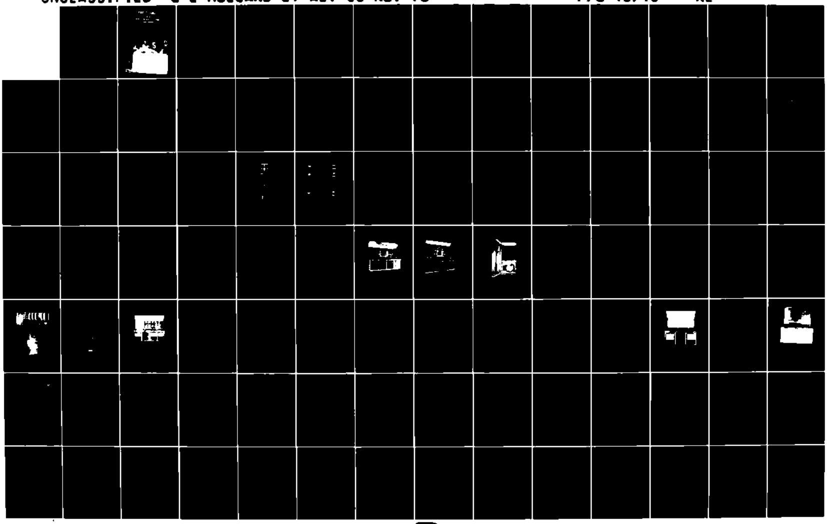

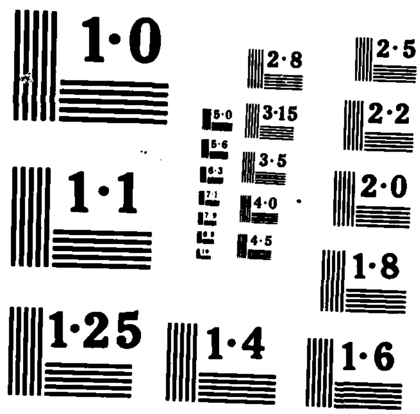
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# PROCEEDINGS

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## FIFTH SHIP CONTROL SYSTEMS SYMPOSIUM

OCTOBER 30 – NOVEMBER 3, 1978

VOLUME 1



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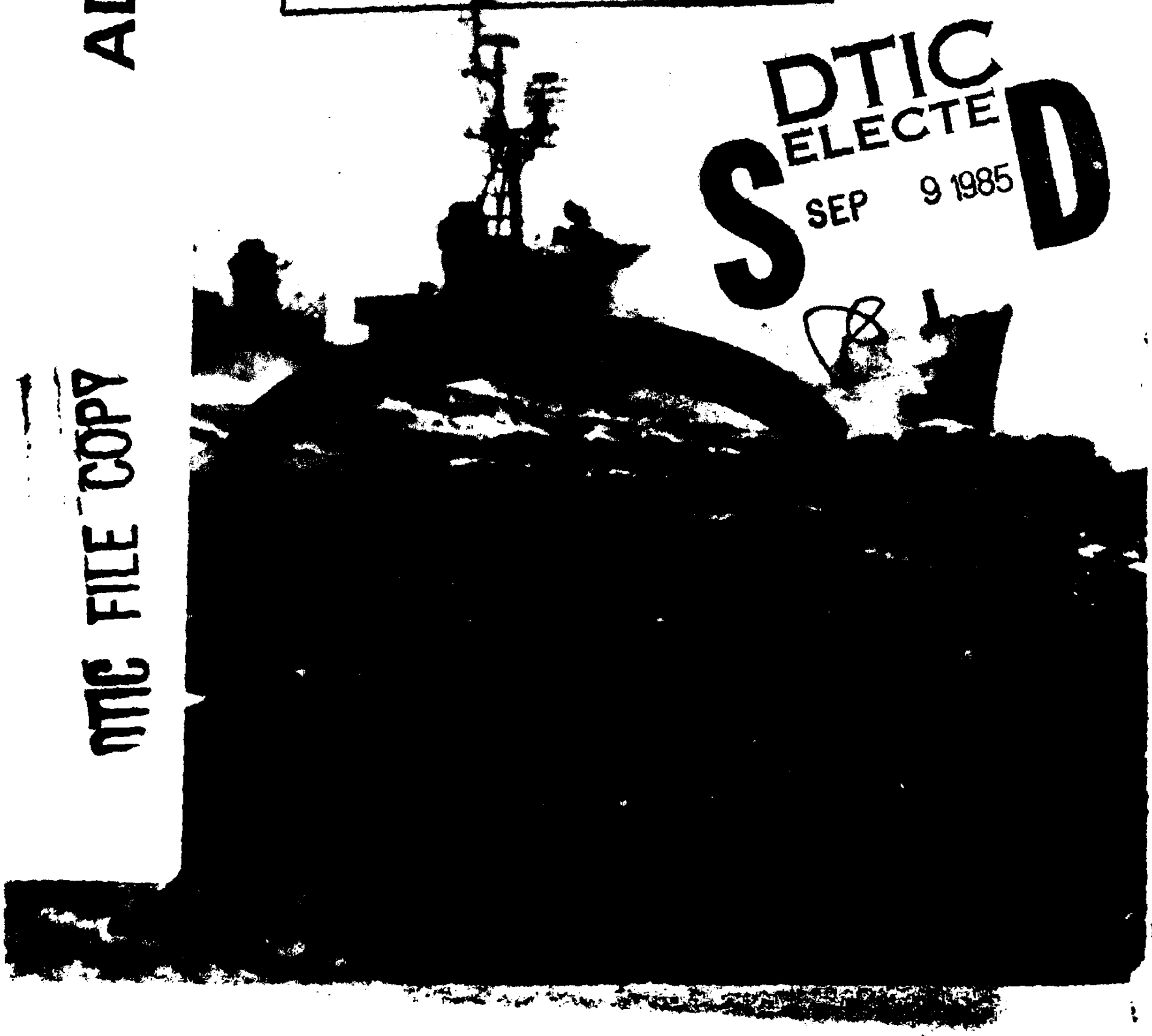

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## FOREWORD

The David W. Taylor Naval Ship Research and Development Center (DTNSRDC) is pleased to present the Proceedings of the Fifth Ship Control Systems Symposium held at the U. S. Naval Academy in Annapolis, Maryland, October 30 - November 3, 1978. This is the fifth in a series of symposia on ship control systems which was initiated in 1966.

The technical papers presented at the Symposium and published in these proceedings cover theoretical studies, comparative analyses, simulations, system design and development efforts and full-scale trials on the subjects of propulsion and steering control, ship automation and integration, navigation and display systems and digital control schemes. Of timely interest is the coverage of the applications of micro-processors to ship control systems.

The response to the Symposium "Call for Papers" was outstanding with more than twice as many abstracts submitted than could be included in the program due to the limited time available for presentations. In addition to the papers presented, we have included two papers from authors who consented to release their technical papers for publication in these Proceedings, although time did not permit oral presentations of their work. The international flavor of this Symposium, as in 1975, has promoted an extensive and interesting coverage of ship control systems as represented by the contributions to these Proceedings made by industry, universities and government of thirteen countries.

These Proceedings are the major record of the 1978 Fifth Ship Control Systems Symposium. The contents indicate the success of the Symposium and provide some insight into the effort that was required to ensure this success. The Symposium organizing committees, advisory groups, Publications Branch, authors, session chairmen, international coordinators, clerical and administrative personnel, and management all provided enthusiastic cooperative support to the many tasks that had to be performed and to the invariably "sticky" problems that arose.

This Symposium has explored, in some detail, a number of specific facets of ship control systems; other areas in the field of ship control will be addressed in the next symposium in this series. As in the past, we hope these Proceedings become a source document on ship control along with the previous proceedings. It is also our hope that we have again provided stimulation to those who will continue to advance this technical field.

WALTER J. BLUMBERG
General Chairman

MICHAEL A. GAWITT
Technical Chairman

## VOLUME 1

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SESSION C:

Chairman: Dr. N. Norrbin
Research Dept., The Swedish State
Shipbuilding Experimental Tank

# INTRODUCTION

by Walter J. Blumberg
David W. Taylor Naval Ship Research and Development Center
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We welcome you to the Fifth Ship Control Systems Symposium (SCSS), the third one to be held at the U. S. Naval Academy in the city of Annapolis. It is a pleasure to be able to extend greetings to so many co-workers in the ship control systems field on this occasion of the fifth gathering to discuss our work and problems. It was here in October 1966 when the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) (then the Marine Engineering Laboratory) sponsored the First SCSS. These symposia, originated and sponsored by DTNSRDC, have provided an international forum for the presentation and exchange of scientific information in a field which has grown increasingly important to the naval community.

The international aspects of these symposia are evidenced in this fifth symposium by the contributions of 144 authors from thirteen countries. In order to provide historical perspective for this Fifth SCSS, we will highlight some of the background material that was included in the Introduction to the fourth symposium in The Hague.

It is particularly appropriate to note the increasing scope of ship control systems. In the past, the ship control systems designer could feel relatively secure in a field which changed very slowly over time. Ship speeds, sizes, and accelerations were relatively stable and slow to change. But today, there is an increase in the types of new vessels. Their characteristics and dynamics are far different and involve scientific disciplines that were not traditionally associated with ship control systems designs. It is appropriate, therefore, that in this fifth symposium, a number of the sessions again be devoted to these new disciplines; to unconventional ships; and to new types of control systems. This continues a practice started in the first symposium -- of discussing the problems as well as the successes of new technology and applications.

The first symposium, held in Annapolis in 1966, included approximately 450 delegates from three countries -- Canada, the United Kingdom and the United States. It had as its theme "Ship Control Systems" emphasizing the integrated systems concept, and the influence of missions on the analysis and synthesis of ship control systems. It brought together, for the first time, those technical personnel who were engaged in the development of ship control systems to meet these broad new challenges, and those ship builders and operators who had to live with the new systems. In total, thirty-three landmark papers were presented on technical areas such as automation, human factors and simulation.

The first symposium can be summed up in the words of the Keynote Speaker, RADM H. G. Bowen, USN, then Deputy Chief of Naval Operations (Development), who put ship control in the broad overall setting of

total ship design. He emphasized the need for greater reliability, maintainability, fault detection, cost-effectiveness, and automation -- and concluded by saying "we are on the eve of great developments".

The second symposium -- which was attended by nearly 500 delegates from the three countries of Canada, the United Kingdom, and the United States, -- was held by the Naval Ship Research and Development Center at the U.S. Naval Academy in 1969. The theme of this symposium was "Propulsion and Maneuvering Control of Surface Ships", with emphasis on ship control automation. Special highlights of the second symposium were the lively panel discussions on: Ship Automation; Control Aspects of Hydrofoils; and Control Aspects of Surface Effect Ships. The results of full scale tests, theory, and simulation were presented by the panels and discussed with the attendees. Of particular interest were papers presented on gas turbine control systems and dynamics, on the DDH 280 control system; and on control of gas turbines and diesel engines with controllable pitch propellers. Also, several important papers were presented on ship automation, maneuvering, and man-machine relationships, on replenishment at sea, and on manning/automation studies.

The first symposium provided the stimulus and interest for further ship control work and the second explored, in more detail, some of the specific areas of importance. The third symposium was held in 1972 in the United Kingdom. It was most ably organized and hosted by the Ship Department, Ministry of Defense, by Captain G. A. Thwaites RN, J. B. Spencer, and D. J. Strong, and held at the University of Bath.

The third symposium was expanded considerably, with representatives being invited from more than 12 countries. Attendance was again excellent, with over seventy papers presented. The interest and needs of the ship control community had grown rapidly in three years, and resulted in double the number of papers presented in the past. The theme of the third symposium was "The Applications of Control Engineering to Surface Ships and their Systems". Papers presented showed the continuing interest in control of gas turbines and automatic control. Presentations on unmanned engine spaces were given -- with special attention to monitoring and maintenance systems. Also, a number of papers were presented on autopilots, related automatic maneuvering and positioning systems, and on precise navigation for survey and other types of vessels. For the first time, superconducting propulsion systems were discussed. The design and arrangements of the Netherlands' guided weapons frigate was of particular interest. There were also some papers on prediction and simulation studies for use in developing control systems. The third symposium can be summarized as an excellent compilation of design and application results which were useful baselines for future ship control designs.

The increased international participation resulted in broader coverage and established the SCSS as a forum filling the needs of the researchers, the developers and the systems designers, and as a place to exchange ideas and compare results.

The Fourth SCSS was organized and hosted by the Royal Netherlands Naval College in The Hague by Commander A. C. Pijcke and Lieutenant W. Verhage under the direction of Commodore J. G. C. Van de Linde, then head of the Naval College. Their enthusiastic approach resulted in a symposium with over eighty papers by authors from eleven countries.

The Fourth SCSS was opened by H.R.H. Prince Bernhard of the Netherlands. The theme of this symposium was "Research in and Application

of Control Engineering for Surface Ships and Their Systems." Special sessions explored in depth the subjects of bridge design and human factors, collision avoidance, applications of modern control theory and digital control, advanced vehicle control systems, simulation and machinery control system dynamics.

Important papers were presented on the impact of automation upon warship design, the development of ship control systems from the initial concept through to the final sea trials, propulsion controls for the Netherlands guided missile frigates, simulation of the DDH 280 class propulsion machinery, and control for directionally unstable ships. In summary, the fourth symposium explored significant control engineering problems in depth from the point of view of theory and applications and provided opportunities for the ship control systems community to continue to benefit from the constructive exchanges of viewpoint.

Since the Fourth Ship Control Systems Symposium, new developments and tests have been conducted in the field of ship automation and control. Increased use of automatic control and monitoring and investigations of plant dynamics have been emphasized. Expanded use of minicomputers and the introduction of micro-processors in shipboard systems have put a new dimension on ship control systems.

The Fifth SCSS responds well to the theme - "Ship Control Systems: recent research and development, design and applications, including the impact and consequences of computer considerations." The papers to be presented here show the results of significant advances in ship control systems over the past three years. The number of papers on propulsion and machinery dynamics and control reflect the extensive activity in this area, much of it based on work reported at the Third and Fourth SCSS. The introduction of computer control and microprocessors brings integrated control and monitoring systems closer, as will be seen in a number of papers. The ffectiveness of simulation as both a primary design tool and as an onboard training method is treated. The subject of ship control systems has become more important as evidenced by the increase in published articles and reports in both technical and general publications, and recent presentations at meetings of technical societies.

From this review of the first five symposia, it appears that the research and development reported to date has resulted in significant applications to ship control problems. This is as it should be. All of us here have the opportunity to take advantage of the ideas presented and the personal contacts made. One of the goals of these symposia is that these ideas will be put to use in future endeavors.

On behalf of DTNSRDC, it is an honor to introduce the Fifth SCSS and to extend our sincere thanks to all who have made this symposium possible: the authors and their organizations who have recognized the value of their contributions, the session chairmen who keep things in perspective, the international coordinators who were always ready when needed, and the symposium chairmen and organizing committees who labored long and diligently.

# AUTOMATION - SALVATION OR DELUSION

by George E. Holland and
Eugene Fitzpatrick, CDR, USN
Naval Ship Engineering Center

ABSTRACT

This paper reviews the development of propulsion plant automation on non-nuclear surface ships of the U.S. Navy, discusses some associated concerns and constraints, and reports on the effort underway to define a rational course to be followed in the future.

## INTRODUCTION

The title of this paper is designed to be provocative and eye catching, but the purpose of the paper is a serious effort to describe a genuine dilemma in the U.S. Navy over control systems. Although stated by different people in various ways, the point at issue is the question of what are the optimum types and degrees of automatic functions and centralized control for ships of the Navy within parameters which, in most cases, are beyond the technical control of the ship designer.

Automation on ships in general is under scrutiny, but this paper is concerned only with automation and central control of propulsion plants. Although communications and weapons control systems have added far more cost and complexity to ships, it is propulsion controls toward which most often are directed charges of either "too complex" or "not enough." It should be noted that the former is being heard with greater frequency and in far more strident tones than the latter.

This paper will discuss automation and central control in today's Naval ships and how they came about. It will then present some of the concerns which have been expressed, and what is being done to address these concerns and reach a rational, realistic propulsion plant control system policy for the future.

The term automation is used quite loosely, and on many occasions incorrectly, by most people. It is a term used for convenience rather than accuracy. It is invoked not only to describe automatic operations but also those which are not automatic but are only centrally monitored and remotely controlled. For clarity the following definitions are used in this paper, except that where automation appears between quotation marks, i.e., "automation," it is being used in the more popular sense:

Automation -

(1) The technique of making an apparatus . . . a process . . . or a system operate automatically, (2) the state of being operated automatically, (3) automatically controlled operation of an apparatus, process or system by mechanical or electronic devices that take the place of human organs of observation, effort and decision.(1)

Central Control -

Remote monitoring and control, either manual or automatic, of equipment and systems from a central location.

BACKGROUND AND HISTORY

Machinery plant "automation" was discovered for the Navy at a very high management level in the mid-1960's. Its implementation was directed on three groups of steam turbine driven, 600 psi auxiliary ships, AKA 113-117, AE 32-35 and AFS 4-7. Backfitted into existing designs, "automation" overtook the forces of evolution which had been at work at least since World War II. Though perhaps painfully slow, the evolutionary process already had been successful in boiler room automation, with automatic combustion control and automatic feedwater control.[2] It is hardly necessary to point out that other types of automation had been quietly in general use in machinery plants for many years, some examples being air compressors, refrigerating plants, distillers and various level control devices. It is also fact that steam turbines and diesels have enjoyed elements of "automation" since the beginning, and therefore long before it was ordered in the sixties.

Understood or not by the ones who directed it, "automation" of the auxiliary ships essentially meant providing a remote operated, programmed throttle control, and gathering together in one location the remote controls and monitoring devices necessary for plant operation. This permitted the watchstander to perform his normal duties underway without leaving his air conditioned enclosure. Extension of the remote throttle control from the engine room control station to the bridge was a relatively simple and inexpensive matter. All of this had been accomplished successfully in the merchant marine, and was the inspiration for the Navy's "automation" movement.[3]

"Automation" was ushered into the auxiliary ships with mixed emotions. The designers were feeling rushed, the operators were apprehensive and management had one great expectation. The big payoff was to be reduced shipboard manning,[2][3][4][5] plus assorted other benefits including fuel economy, greater operability and less corrective maintenance.

It was almost an article of faith that "automation" would reduce manning. It was inferred that if the merchant marine could make significant manning cuts by "automating" the propulsion plant, well then so could the Navy. Once this idea was accepted (directed) it was easy enough for design engineers to find other good things about "automation." Fuel savings would be realized due to more efficient plant operation, made possible by the faster and more precise sensing and response of the automatic controls. It followed that if the plant operated more efficiently, without the more radical swings occasioned by manual operation, then there would be fewer breakdowns and thus less maintenance.

While such reasoning may seem naive today, in the sixties it sounded good, and was very much in the spirit of trying to do something constructive about the stated need to reduce shipboard manning. To the credit of the design engineers at the time, they saw clearly the need for "automated," minimum-manned ships to have higher rated men, better trained and more highly skilled, both for operation and maintenance.[2][3] Cross-training was advocated as a way to produce Navy

personnel as much as possible like their merchant marine counterparts. The ship designers saw their job as providing an "automated" plant which could be operated and maintained by fewer, but highly qualified people. With the emphasis given "automation" at high levels it was only natural for the designers to assume that those who were responsible would produce the necessary people, i.e., those who were sufficiently skilled and trained to take full advantage of the labor saving tools to be provided.[2][5] This, of course, would have required a revolutionary approach to the personnel problems of selection, training, rate structure, assignment, work habits and retention.

Unfortunately there was no understanding voice in the Navy's technical community raised convincingly to put the matter of automation, central control and manning requirements into credible perspective. As would be expected, "automation" philosophy grew over the years to include, among other features, automatic pump sequencing, automatic data and bell logging, automatic alarm scanning, automatic burner controls, and automatic load shedding and paralleling of generators. The emphasis on highly "automated" ships and reduced manning has carried over, in the seventies, to combatants as well as auxiliaries. Two, new classes of combatant ships, FFG 7 and DD 963, have entered the Fleet recently, both powered by gas turbines, with both following the same general control system and manning philosophy as the "automated" steam ships. Introduction of gas turbines has presented new controls systems problems, but gas turbine proponents have been heard to declare that gas turbines are inherently more automatable than steam plants, and also that significantly fewer personnel are required. The remainder of this paper will discuss some of the questions which have been raised about the delivery of "automation's" promises, and what is being done about them.

## CONCERNS AND CONSTRAINTS

The major impetus behind propulsion plant "automation" in the Navy has been the promise of reduced manning, a concept which originated in the commercial marine industry. Predictions of personnel reductions in propulsion plant watchstander requirements of highly "automated" Navy designs over similar designs with limited "automation" have ranged from 60 percent for a mid-1960 design to 75 percent for a recent design. There are indications that propulsion plant watchstander requirements for highly "automated" ships tend to grow over the years. Suspected reasons for this growth include lack of operator trust in the automatic system, failure of the systems to operate in the automatic mode for various reasons, on-the-job training requirements necessitated by the lack of a pool of skilled operators, and ingrained conservatism. In addition, even if the predicted watchstander requirements were met, it is hypothesized that this would not result in an overall reduction in propulsion plant manning because of the existing shipboard maintenance requirements.

If it is fact that overall manpower is not reduced with highly "automatic" propulsion plants, then it seems clear that any improved performance in the areas of safety, reliability, response-time and efficiency must be balanced against the added maintenance burden, logistics support problems, manpower and skill availability, training requirements and overall cost and operational implications in determining the degree of "automation" to incorporate. It may be that the constraints imposed by these latter considerations are so formidable as to dictate that "automation" only be incorporated in Navy propulsion plant designs where technically required for equipment and personnel

safety, or, if incorporated for other compelling reasons, that the "automation" be the absolute simplest necessary to perform the assigned task. This, of course, in addition to propulsion plant "automation," applies equally as well to remote bridge control.

Skill availability is a critical concern in the Navy today. Navy-wide the requirements for technically trained personnel are higher than recruiting, training and retention programs are providing. The demand for skilled personnel to operate and/or maintain aircraft, sophisticated weapons systems and other command and control equipments is on the increase. In many of these applications there are no alternatives to the complexity and level of automation specified. This seems to suggest that "automation" should be used in other ship systems only to the degree required by hard technical considerations.

Ashore training support facilities and training personnel are also a major constraint. Ashore training support in the Navy is currently being reduced, thereby necessitating an increase in on-the-job training afloat. But the current policy of highly "automated" propulsion plants does not allow for the on-the job training billets normally found, but not necessarily recognized as such, in plants with limited "automation". The personnel needs of highly "automatic" plants run almost exclusively to technically qualified operators who can immediately step in and contribute. The requirement for increasing on-the job training is, therefore, inconsistent with today's concept of minimum-manned, highly "automatic" propulsion plants.

## APPROACH TO RESOLVE CONCERNS

A Navy review is currently in progress to evaluate current propulsion plant "automation" policy to ensure that designs being introduced into the Fleet are not overly complex or overdesigned. The objective of the review is to conduct a critical analysis of current policy and to formulate recommendations to establish updated policy that can be implemented practically and effectively into our designs within present day constraints. These constraints include those of training support facilities and personnel; skilled personnel availability; ashore and shipboard maintenance capability; and existing maintenance strategies, documentation, supply support, enlisted rate structure and design philosophies. While it is clear that the technology exists to design very sophisticated "automatic" propulsion control systems, it is also clear that the related biotechnology must be consistent with the above constraints and, as a result, full utilization of automation technology in all likelihood will not be achieved. The problem becomes one of where to draw the line to best utilize our present and projected resources.

In order to determine if propulsion plant "automation" has achieved the goal of reduced manning, ship manning data for existing ships with highly "automatic" propulsion plants will be compiled commencing with the conceptual design to the present. Where possible these manning data will be compared to data from ships of the same class with more limited "automatic" propulsion plants. Other propulsion plant "automation" data to be collected and analyzed during the review will include formal inspection deficiencies, maintenance information, supply support data, training data and operational data. Shipboard visits to ships representing seven classes and three different types of propulsion plants will be included.

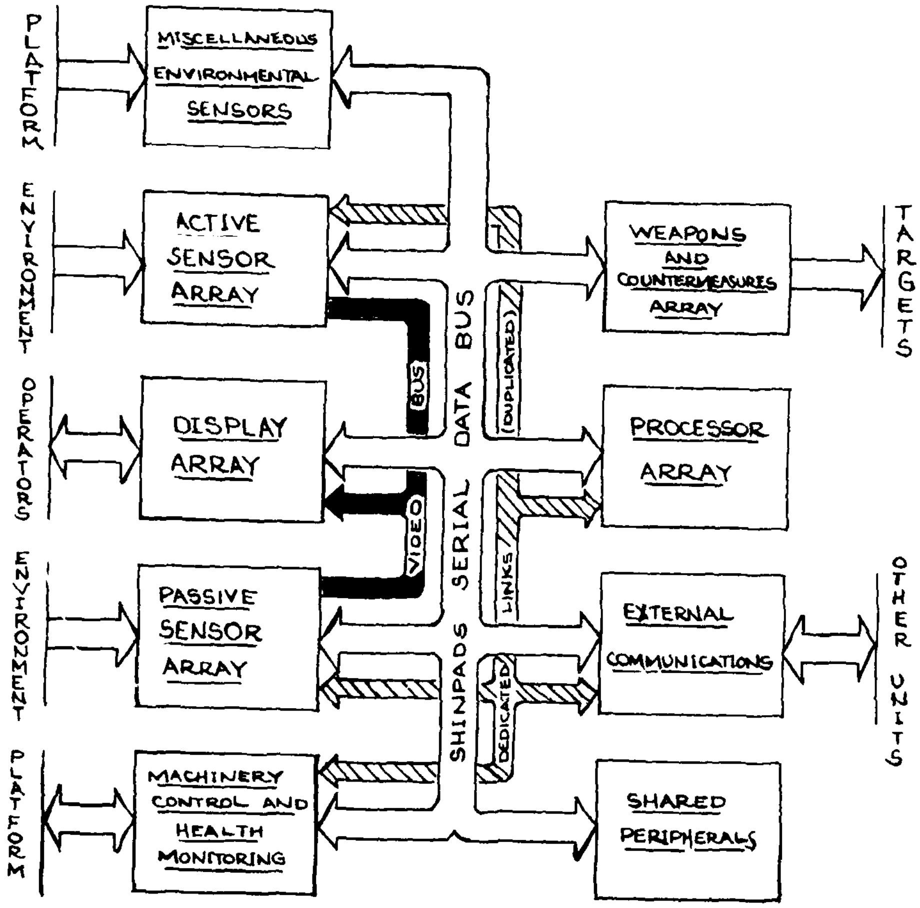


Figure 1. SHINPADS Top Level Diagram

When one examines the electronic equipment on a ship it is apparent that modern control systems, whether they be applied to a propulsion application or a combat system, are essentially assembled from similar components. If this is so why have different systems evolved? Is it because the problems being solved are basically different or could it be that they were sponsored by different bureaucracies? The reason for such differences is no doubt a mixture of the two however while the balance was perhaps originally very much influenced by technological differences it is suggested that electronics technology has developed to the point where the balance has shifted and the bureaucratic process is now the driving force. Furthermore not only do authorities concerned with propulsion and combat systems often appear to be proceeding in parallel but separate paths but subsystem developments within these system areas appear to be developed in such a manner.

## BACKGROUND

In an attempt to address this problem within the Canadian Forces (CF) the Director of Maritime Combat Systems (DMCS) at National Defence Headquarters (NDHQ) directed that a committee be formed to examine the integration problem. The small size of the CF Naval Element is usually considered to be a handicap however in this instance it proved to be an advantage. Due to the small size of NDHQ staffs the necessary marine systems engineers and naval architects responsible for other ship system areas were close at hand, accustomed to working with combat systems engineers, and could therefore function as effective committee members.

Many ideas and approaches were put forward during the deliberations of the group, however a paper (1) which addressed the whole problem from an electronic architecture point of view has become associated with the work of the group and the SHINPADS acronym. It is an understatement to say that this paper drew upon the opinions of all group members and contains many ideas not necessarily originated by the author.

## BASIS OF THE CONCEPT

A top level view of SHINPADS can be gained through examination of Figure 1. Any surface and air subsystem developer might immediately ask where the block representing his equipment is. The basis of the concept is that there really is not any such subsystem, instead the components such as sensors, displays, computers and weapons are all considered part of the global ship resources. Although at any instant a set of such resources may be acting in concert to carry out the function of a classical surface and air subsystem a short time later a different processor and display could be doing the same task. It may be enough to make all past gunnery officers turn in their graves but at the same instant the processor purchased as part of a weapons development project may be running a propulsion machinery control program.

Despite the fact that Figure 1 contains equipment type blocks it is important to point out that SHINPADS is not a particular hardware system. It is instead a concept -- a concept of ship integration. The concept is based upon three ideas:

a. a distributed system approach;

b. standardization of devices, software, and interfacing; and

c. a ship's "spinal cord" or data bus.

Distributed System. Due to the high price of the first digital computers designers were forced to bring all information to a central point (namely the computer) in order to provide affordable systems. Although the cost of such devices later fell drastically the tendancy was to build more powerful and larger

# SHINPADS
## A SHIP INTEGRATION CONCEPT

Commander James F. Carruthers
Canadian Forces*

ABSTRACT

This concept of ship integration has been entitled SHINPADS - an acronym for SHIPBOARD INTEGRATED PROCESSING AND DISPLAY SYSTEM. The impetus for development of the concept is explained and a ship system architecture encompassing all areas of computation and control including combat systems, propulsion/machinery system, and extending to administrative support systems is developed.

This design approach has been made possible by the rapidly developing electronic technologies associated with minicomputers, microprocessors, advanced display techniques, and signal multiplexing. The application of these technologies to system integration by distributing intelligence rather than centralizing it is demonstrated.

Such an approach predictably raises organizational problems as traditional boundaries between ship propulsion and combat systems are broken down, however the distributed system concept is one of the cornerstones of the design approach and the elimination of such boundaries is a necessary objective if effective ship integration is to be achieved.

Two other key fundamentals of the concept are device standardization and replacement of the present mass of ship's wiring with a linear bus structured "ship's central nervous system". The characteristics of a standard display which is capable of meeting the needs of all users and the specifications of the SHINPADS data bus which carries all ships data are examined.

Although it will affect the organizational divisions which many find comfortable it is suggested such an approach is necessary if significantly lower life cycle costs are to be achieved while providing increased onboard reliability, redundancy, and survivability.

INTRODUCTION

> SYNERGISM -- syn'er-gism -- Cooperative action of discrete agencies such that the total effect is greater than the sum of the two effects taken independently (WEBSTERS NEW INTERNATIONAL DICTIONARY)

In a compendium of technical jargon and buzz words terms such as integration, modularity, redundancy, etc abound. The word synergism, although obscure enough to be considered a candidate for inclusion in such a compendium, has never really made it. This paper is not in support of the upgrading of synergism to the exaulted status of buzz word. Rather it is in support of upgrading our ship design ideas such that the term synergism can accurately be applied to them. If any one word had to be selected as best representing the SHipboard INtegrated Processing And Display System (SHINPADS) it is hoped that synergistic would be picked.

* The opinions expressed in this paper are those of the author and do not necessarily reflect the policy or position of the Canadian Forces.

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## CONCLUSION

As technology advances and the need for manpower reduction is emphasised, pressure to use more automation increases. Indiscriminate automation can have unforeseen undesirable consequences, and it is for this reason that, before embarking on the design of new control systems, the comprehensive research programme described briefly in this paper was carried out. Those systems which are being designed using the results of the research programme, and which it is intended to fit in the next generation of surface ships of the Royal Navy, will make use of micro-processors and digital technology. A common high level programming language will be used with a modular approach to software control and testing; and systems will be evaluated in a shore test facility. Significant advantages should accrue from reduced initial and life cycle costs, increased availability and improved invulnerability to damage. Furthermore it should be possible to accommodate a reduction in manpower from present levels should this become a requirement, or a necessity.

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The potential advantages of such an arrangement are that the systems should be cheaper to buy, install and maintain, and better system performance should be achieved by increased operator effectiveness.

Propulsion Control System

Applying the above concept to the propulsion system as an example, but noting that the principles are equally applicable to other systems, suggests that the system would be somewhat different from that in the Type 42 which has all the electronics in the SCC. Control signals from the Bridge via the SCC, or the SCC itself, would be passed to the system control units in the machinery spaces. The system control units would then operate in concert the individual plant control units. In normal Bridge operation the Quartermaster would move the control levers (one per shaft), and there would be a watch-keeping crew of perhaps two men in the SCC responsible for all ships machinery.

Primary surveillance information is that necessary to operate the system, and it would be permanently displayed in the SCC as part of the integrated display system mentioned previously. Faults would be immediately indicated and where possible the operator would re-configure the plant to isolate the fault. Various configurations would be possible down to the lowest level of manual control at the plant itself, which would, of course, usually necessitate the calling-up of additional personnel. Secondary surveillance information is that required for more detailed diagnosis of a problem, and subsequent direction of a maintainer to the faulty equipment. This information would be available to the operator in the SCC on demand at a Visual Display Unit.

One of the advantages of the type of system just described would be its adaptability to different propulsion configurations such as COGOG, COGAG or CODOG (Combined Diesel or Gas). This adaptability is achieved by defining the functions required in each of the plant control units, system control units and man-machine interfaces, and then keeping the electronics for each individual function completely separated, both as regards hardware and software, except for common power supplies. Thus, should it become necessary to make a change because of a different ship requirement, or the implementation of a new technology, one or more functional units could be changed without affecting the others.

Some further advantages should be:

a. Increased invulnerability to damage because the system is not centralised in one location.

b. Increased operator effectiveness, and hence system availability, because of more viable modes of degraded operation.

c. Easier diagnosis and maintenance because of the distributed system concept, and the functional breakdown within the system.

d. Reduced upkeep costs because functional design will make it easier to replace obsolete equipment.

e. Potential for manpower reduction.

complexity-effectiveness trade-off exercises for machinery control and surveillance systems; further detail can be found in the paper by Dr French and Mr Dorrian (ref 11).

The control philosophy at present proposed for the propulsion system is essentially conventional, although, as noted elsewhere, it is thought that there is sufficient flexibility to permit the incorporation of the results of later research. One such possibility is the use of an adaptive multi-variable control technique to exploit the flexibility and power of micro-processors. To assess the possible advantages to be gained, if any, a research item is now underway, simulation models are running, and various control configurations will be studied. Having just mentioned micro-processors for the first time in this paper it is opportune to note that some software studies do form part of this research work, but perhaps of greater importance is the effort being put into achieving, if possible, a common computer strategy for real-time shipborne digital systems. The results of this work are to be found in the paper by Lt Cdr Whalley (ref 14).

## Component Level and Design Technique Studies

Research under this heading is aimed at providing information on new components for use in operator and machinery level applications. There is continuing work on the evaluation of display devices and associated equipment in terms of cost, human factors and environmental suitability; criteria for actuator selection are also being developed. The evaluation of a typical micro-processor application has also been undertaken, as reported in the paper by Messrs Bruce and Baxter (ref 15). System identification also forms part of this package, and a multi-frequency technique has been developed using Schroeder-phased harmonic signals which may have applications in the analysis of systems, particularly those exhibiting unusual characteristics (ref 16).

## OVERALL SYSTEM CONFIGURATION

The concept arising out of the machinery control and surveillance research programme is that future systems will be based on a digital technology using micro-processors and multiplexing in a distributed configuration, as opposed to the present centralised arrangement. The machinery will be divided by function, that is propulsion, chilled water, electrical generation etc, each interfacing with a data multiplex ring through its own dedicated system control unit. These control units will use identical processors and software organisation, but will be programmed differently depending on the functional requirement. As it is a distributed configuration the dedicated control units will be sited near the machinery which they control.

The display and control positions will be much reduced in size from consoles in use at present, the same ergonomic design considerations will be employed on different classes of ships, and similar hardware used. Mimic diagrams will be used for permanently displayed information, and visual display units will be used for information not required at immediate notice such as that necessary for maintenance or diagnostic purposes. Thus in the SCC it is intended to have a system which will cater for propulsion, auxiliaries, electrical generation and distribution, and damage control as an integrated whole (ref 10).

reduction in the quality of recruits available means that designs which reduce the number of operators, but require an increase in the number of skilled maintainers, will not be acceptable. However, past experience indicates that this guideline and a. above are incompatible.

c. Ships complements will be fixed and defined in any new ship's Naval Staff Requirement, albeit after initial discussion with DGS; thereafter DGS will be required to design to these figures. This is a departure from existing practice where complementing is largely carried out after a ship's design has been outlined, and is a reflection of the technological advance of recent years, which has largely removed the technical constraints on the degree of automation that can be practically provided.

d. Shore training time, and with it training costs and manpower, must be reduced. Designers of systems should therefore consider the inclusion of onboard training facilities within their equipment. For example, the installed control system could be switched to a simulation of the machinery for training purposes, whilst the ship is alongside with her main machinery undergoing maintenance.

Operator and Interface Level Studies

Operator trainer selection criteria. The Naval Marine Engineering School at HMS SULTAN has had simulator training facilities since 1968, and these were described in a paper presented at the Fourth Symposium (ref 8). When the Type 22 and Command Cruiser were ordered a study was inaugurated to provide advice on the most cost-effective training aids. The outcome of this study is reported in a paper being presented at this Symposium by Cdr Locke and Lt Cdr Phelps (ref 9).

Man-machine interface. A statement of requirements for a man-machine interface depends upon the system tasks, the command structure, the manpower available, human factors and training requirements, taking into account available control space, siting, configuration, and communications. A continuing research programme is aimed at producing a rigorous design method that can also be used to assess cost-effectiveness. Progress to date is reported in another paper being presented at this Symposium by Lt Cdr Steinhausen and Mr Orton (ref 10).

Machinery Level Studies

Based on research undertaken under this heading a digital propulsion control system has been defined, and work will begin soon on the construction of a demonstrator version. System details can be found elsewhere in this paper and others being read at this Symposium (refs 11, 12). The demonstrator version will be evaluated at the National Gas Turbine Establishment (NGTE) and a description of the proposed facility for evaluation is given in the paper by Mr Duberley (ref 13). The evaluation centre will also make use of mathematical models developed in work packages of this research item. Simulation is a continuing process but validated models are available of gas turbines, transmission plant and controls, hull and propeller dynamics. The functional and reliability requirements study has established a numerate methodology for conducting

d. Surveillance equipment costs are generally greater than control equipment cost, some 35% in the full automation option.

The design implications of these conclusions are:

a. In the Marine Engineering Department the levels of manpower in current new construction ships, to fulfil similar roles, cannot be justifiably reduced much further.

b. Sophisticated surveillance is costly and techniques used in engine health monitoring, such as trend analysis, have to be justified at the plant level, on the grounds of reducing the number of overhauls and the likelihood of plant damage.

Vulnerability. Measures taken to minimise the effect of damage tend to be expensive, and the work was designed to assess whether the existence of modern weapons should change these measures, and hence the policy for machinery control. In the extreme it could be argued that ship designs should ignore invulnerability considerations on the grounds that one hit by some modern weapons will incapacitate a ship completely. However, work continues and at present a coarse model is being used for system vulnerability studies which is thought sufficient for use in the early design stages, even though it is perhaps not strictly valid. Explosion damage data are not available to support more complex models. Studies to date serve to confirm the obvious, namely:

a. Separate independent systems carrying out the same function are to be separated one from another by the greatest distance possible.

b. Any one system should as far as possible be concentrated in the same area of the ship.

c. Important systems should be designed to be still operable, albeit in a degraded mode, even if part has been damaged.

d. Significant savings could be made if it were found possible to relax current standards of invulnerability. Individual equipment costs can increase by three times just to meet naval shock requirements.

Manning. All the work on manning has been carried out intramurally involving sections of the Director General Ships department (DGS) and the Director General of Naval Manpower and Training department (DGNMT). Because it takes some ten years for manning policy changes to work through to the Fleet, and because of other factors which in the short term affect recruitment and re-engagement, it has not been possible to predict with absolute confidence the manning situation for the 1980s. Nevertheless the following guidelines as they affect the machinery control are evolving:

a. Ship's companies will continue to decrease to match a predicted reduction in recruitment arising from the decrease in the birth rate, and the increase in the numbers proceeding to higher education.

b. Designs must cater for an overall lower grade of skill than that which exists at present. This is necessary because the

Table I. Research Programme Activities

| | | |
|---|---|---|
| Ship Level | 1. | Ship cost and configuration studies |
| | 2. | Vulnerability studies |
| | 3. | Manpower utilisation studies |
| Operator and Interface Level | 1. | Operator trainer selection criteria study |
| | 2. | Man-machine interface studies |
| | 3. | Data transmission studies |
| Machinery Level | 1. | Future generation control system studies |
| | 2. | Dynamic machinery simulation studies |
| | 3. | Machinery sequential control studies |
| | 4. | Functional and reliability requirements studies |
| | 5. | Study of alternative control system philosophies |
| Component Level and Design Techniques | 1. | Processing and display studies |
| | 2. | Actuator selection criteria study |
| | 3. | Microprocessor application evaluations |
| | 4. | System identification studies |

The original intention was to progress through the research programme eventually arriving at the definition of the future machinery controls. In the event new systems are being developed even though some of the research items are not yet complete. However, it is thought that the designs are flexible enough to cater for any foreseeable changes future research might recommend. The results of some of the research work are presented in the following paragraphs.

Ship Level Studies

Cost and Configuration. The cost implications of five different levels of automation in a ship with a defined role were considered. The levels ranged from a 'no automation' option with a large ship's company, to a 'full automation' option with a small ship's company. Weapon systems were not included. Life cycle costs and capital costs were arrived at in very broad terms.

The conclusions reached were:

a. The initial acquisition costs of the controls for the full automation option are three times those for the non-automated option.

b. Life cycle costs are dominated by manpower.

c. Automation at the lowest levels gives rise to the biggest savings.

itself (via the gas turbine and the controllable pitch propeller actuator). The Type 21 frigates are similarly controlled. Operating experience in the first ships fitted with electronic control systems, (HMS SHEFFIELD and HMS AMAZON), is described in a paper presented at the Fourth Symposium (ref 6). Ships with this type of system will form the bulk of the Royal Navy from about 1983 onwards when the increasing number of ships with electronic controls will exceed the decreasing number of ships with pneumatic or other form of control. However, in order to take advantage of new electronic technology, and to avoid obsolescence problems, it was appreciated in the early 1970s that new systems would have to be designed for the next generation of surface ships, which will still be operational in the twenty-first century. Furthermore, it was also appreciated that systems designed now for installation in the 1980s should, where possible, use technology which it is thought will be appropriate at that time. The case for the automated, advanced technology, high integrity warship was made in a paper presented at the Fourth Symposium (ref 7), and about the same time a comprehensive machinery control and surveillance research programme was initiated. This research programme, some of the results achieved, and the progress towards the development and evaluation of new systems will be described in this and other papers presented at this Symposium.

MACHINERY CONTROL AND SURVEILLANCE RESEARCH PROGRAMME

Control and surveillance equipment forms the interface between the man and the plant, and essentially most of the functions performed by men, certainly predictable and routine ones, can theoretically be fulfilled by controls hardware. Thus, there is an interchangeability between men and controls and this marks out the need for a different approach to the design of machinery control systems to that required for other ship equipments. It involves the widest issues of ship operation and maintenance, ship vulnerability, and ship complementing in arriving at decisions as to which functions should be automated, and which should not. At the highest level the machinery control problem is one of determining the correct balance between men and automation to ensure that all the functions such as anti-submarine warfare, air defence or earthquake disaster, for example, can be carried out in the optimum manner. It is significant that the reduction of manpower in the Types 42 and 21 has created problems in such labour intensive activities as ship husbandry and the provision of fire parties. The lesson to be learnt from this is that reduction of manpower in one area can generate problems in other areas, and that automation is a whole ship problem, and should be considered as such.

Appreciation of the impact of automation on the whole ship has featured prominently in the machinery control and surveillance research programme, together with the realisation that automation would creep into ships in an unco-ordinated fashion if a decisive design policy was not adopted. The aim of the research was to determine the optimum balance between man and hardware for any new ship design, and then to define the hardware necessary to match the balance. The programme was not related to any particular ship, and at the outset four areas of research were specified into which work packages were, and still are, allocated. These areas of research are designated ship, operator and interface, machinery and component. A list of work packages is given in Table I where it can be seen from the titles that they range from the consideration of broad concepts to specific hardware design.

# SHIP AUTOMATION IN THE ROYAL NAVY

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## ABSTRACT

A comprehensive machinery control and surveillance research programme was initiated in the early 1970s to determine the optimum balance between men and hardware for any new ship design, and subsequently to define the hardware necessary to match that balance. The scope of this research *programme*, and the progress towards the development of suitable systems is outlined in this paper. Reference is made to more detailed papers being presented at this Symposium.

## INTRODUCTION

In the 1950s it became the practice in the Royal Navy to control the main propulsion machinery of a ship from a Machinery Control Room (MCR) separate from the machinery being controlled. This arrangement was designed to provide a centralised watch-keeping position which could be fully protected from the hazards of radiation and gas contamination. Additionally the conditions for watch-keeping personnel were improved, and fewer men were required specifically for watch-keeping duties. In a paper presented at the First Ship Control Systems Symposium (ref 1) Cdr Wills gave details of the MCR layout, and described the control systems of a COSAG (Combined Steam and Gas) ship typical of those operating at that time. The propulsion machinery controls were pneumatically operated, and the analysis and simulation of the control systems was described in another paper presented at the same Symposium (ref 2).

In 1965 it was decided that further development of steam propulsion could not be justified, and that future ships would be driven entirely by gas turbines. Electronic control systems, unmanned machinery spaces, comprehensive hazard warning systems, and a maintenance policy of upkeep by exchange were also to be introduced where practicable. A paper was presented at the Second Symposium in this series (ref 3) in which details are given of the last COSAG ship built for the RN, the all gas turbine trials ship HMS EXMOUTH, and the COGOG (Combined Gas or Gas) Type 42 Destroyer in which electronic controls were introduced. The Type 42 control system is described in greater detail in another paper presented at the Second Symposium (ref 4). It will be appreciated that an almost revolutionary decision such as that taken in 1965 takes years to assimilate and implement, and it is not surprising that no significant developments were recorded in the position paper presented at the Third Symposium (ref 5).

The Type 42 control system is basically frequency analogue with the electronics in the Ship Control Centre (SCC). The propulsion machinery can be controlled from the Bridge, the SCC, or at the plant

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A final report will be issued upon completion of the data evaluation by the Naval Ship Engineering Center. This report, due in early calendar year 1979, will include recommendations concerning the need for and approach to providing propulsion "automation" in Navy ships. From these recommendations future Navy propulsion plant "automation" policy can be formulated.

SUMMARY

Since the mid-1960's the U.S. Navy has been embarked on a course of increasing propulsion plant "automation." From the beginning its major selling point, rightly or wrongly, has been reduced manning. The labeling of more recent designs as overly complex by some, thereby widening the gap disproportionately between "automation" and the Navy's ability to operate and maintain these systems and equipments, has sparked an objective, overall review of the current Navy propulsion plant "automation" policy. There are indications that the major objective of reduced manning is not being achieved in some designs and can only be achieved in others by changing traditional maintenance strategies. This suggests that other considerations be weighed carefully in determining the degree of "automation" to incorporate. The Navy review will evaluate data to determine whether reduced manning has been achieved. The review will also provide the basis from which an updated, realistic propulsion plant "automation" policy can be developed within existing constraints, which in most cases are not technical in nature.

computers rather than to deliver computers of the same capability at less cost. Consequently the growth of centralized systems has continued unabated with the concurrent development of organizations dedicated to the care and feeding of the large machines. It is suggested that the technical requirement for such centralization no longer exists and the availability of low cost but capable digital processors allows the designer to consider spreading the processor around and putting it out in the areas where it is most needed. Such an approach has been termed distributed processing.

The distributed system suggested in SHINPADS should not be confused with a federated approach sometimes defined to have distributed processing. In a federated system several processors carry out different tasks as part of their subsystems however in addition to being dedicated they are controlled from some central point or computer. In a federated system the overall ship system capability can be lost by loss of the federating computer which other computers must report to. The distributed approach of SHINPADS is based upon geographical distribution, functional distribution, and distribution of control.

Once the concept of many smaller processors replacing a large one is accepted it becomes readily apparent that they can be dispersed throughout the ship such that any single hit cannot possibly eliminate all of them. Thus the term geographic distribution. Ship control involves many disparate functions which in the recent past have often been carried out in a centrally located processor. For example the monitoring of main engines, engine control, auxiliary control, propellor pitch optimization, etc. may have all been carried out within the processor which serves the machinery control room. As a result one processor contains several different types of programs and the interaction of the subprograms, their scheduling within the computer, etc. becomes a major consideration. However when numerous inexpensive computers are considered functions may be assigned to processors on a one to one basis. This is termed functional distribution. Finally, perhaps the greatest drawback of centralized and federated architectures is the problem of putting all the eggs in one basket. These approaches contain a single point of control, which if destroyed cripples the ship or at the least eradicates the federating part of the system. In the SHINPADS approach control may be carried out by any processor/mode and will move around. Thus no element is crucial and a comprehensive redundancy of control exists. Thus the idea of distribution of control.

Such distribution of intelligence or processing, if it is to progress beyond the concept stage, must be supported by hardware. In distributing the major tasks the AN/UYK-20 minicomputer was found to be suitable. But for distribution of tasks such as sensor monitoring within a compartment or control of auxiliaries a small inexpensive computer was required. It was also considered necessary that this small computer appear to the programmer exactly like a AN/UYK-20 would. To fulfill this requirement a microcomputer emulation of the AN/UYK-20 called the AN/UYK-502 is being developed. In its minimal form it is a single six by nine inch card which can be inserted into the machinery designers control cabinet.

Standardization. An important part of the design requirement was life cycle costs. Therefore the savings which could be gained through standardization became a prime target. Although decisions are frequently made on the basis of initial purchase price, due to attempts to fit acquisition within a budgetary limit, the costs associated with support in the field are many times the initial purchase price. The cost of sparing, training, documentation, and software were the driving force in SHINPADS discussions.

A look at Canada's most recent destroyer design (the DDH 280 class) should be enough to convince any observer that Canada's ships are truly NATO ships, with major equipments from almost every NATO country. Any plea for NATO standardization falls on sympathetic ears in Canada. Consequently the work of NATO group NIAG SG 6 regarding interface standardization (2) was included as a SHINPADS design factor. The criteria as applied required all devices to plug into the system via NATO interfaces as proposed by STANAG 4153 (3).

The effects of such a philosophy of standardization can be illustrated by two examples, one based on off-the-shelf equipment the other based on a development to meet the requirement.

The choice of processors was limited to relatively few options when the field was limited to military qualified minicomputers (4). Although other processors outperformed it in almost every area the AN/UYK-20 computer was selected. Despite the fact that individual project managers might find a computer better suited to their particular application the AN/UYK-20 had one outstanding quality. Canadian manufacturers who might develop equipments to meet our specifications should be able to look to wider markets. The UYK-20 had been adopted by the USN as a standard, was being introduced by other NATO navies, and was being fitted by Australia and Japan. If standardization outside the CF was to be considered a factor there really was no other choice.

The requirement for a standard display which would not only meet the machinery control requirements of alphanumerics, graphics (MIMIC, system diagrams, etc.), TV, and IR, but could also provide operational displays of radar, sonar, etc. was judged to be unsatisfied when off-the-shelf equipments was considered. Consequently one of the developments necessary for support of SHINPADS was the development of a display technology capable of supporting these modes of operation. The displays utilized in ship control applications are thus the same as those utilized in the combat systems area. Anything less than shipwide standardization is something less than standardization.

Data Bus. One of the basis of this distributed approach is the concept that local resources become global resources. For this to happen a singular means of data distribution is necessary. The thought of all the ships data being passed through a single conductor may not seem reasonable however examination of the worst case data rates for a typical frigate yields a throughput requirement of somewhat less than three million bits per second (MBS) (5). Since a 10 MBS data rate is comfortably achieved it appears reasonable to expect that a single condu tor could replace all the ships data cabling.

A data bus is therefore being developed. It will replace all the ships cabling except for a network which will carry all voice and the ships power distribution system. Although the present SHINPADS Data Bus design utilizes triaxal cables with NATO low level serial signal standards, the design is directly compatible with fibre optics. Aside from providing a single medium for data exchange the data bus aids ship installation, and any subsequent refit or conversion (6). The data bus is transparent to the user with the user "plugging in" via a single connector. In this manner equipments can be developed at a manufacturers plant utilizing point to point interconnections and then plugged into the data bus aboard ship. Backward compatibility with older point to point wired ships is also thus ensured (7).

Since the bus cables are small, alternate buses can be configured to run down the port and starboard sides, along the keel, etc. so as to provide back up. Two cables are required, one for control and one for data. The bus is capable of using any available cable for any purpose with a maximum of six cables. Thus the entire ship set of interconnecting cabling can be replicated by running another conductor - such duplication would be unthinkable with present point-to-point techniques.

## PROCESSING AND DISPLAY

The application of this concept to the ship control system can perhaps be best illustrated by examining the computer and display realizations. A typical frigate sized ship must have approximately 14 minicomputers and in excess of 50 microcomputers. A SHINPADS type system minicomputer array would resemble that shown as Figure 2. Each AN/UYK-20 minicomputer would have an associated AN/USH-26 cartridge magnetic tape unit which would contain copies of several program alternatives. Programs would be loaded on command from the bus or under local control. In addition programs could be loaded from disk via the data bus. Examination of Figure 2 reveals that the only difference between the engine control computer and a fire control computer is the labelling on the diagram. In practice the only difference will be the software loading, therefore any computer can take over the task of engine control. In this manner failure of any computer will not necessarily mean that a capability is lost. Tasks can be successively shed as computers fail or are knocked out. Thus the overall ship system will slow down rather than abruptly halt.

The SHINPADS Standard Display (SSD) can be configured by simply adding modules. Thus in examining Figure 3 we see that those displays with a processor and alphanumerics/graphics capability, termed synthetic only displays, can be considered a subset of the video displays. With a generalized graphics capability and touch sensitive CRT surface and SSD can replace customary dedicated meters and buttonry customarily associated with ship control consoles. All information is available at all displays so that in addition to providing life cycle cost reductions the architecture provides tremendous redundancy.

## DATA GATHERING

Figure 4 depicts the data gathering system. In general an AN/UYK-502 microcomputer will act as an embedded part of a ship health monitoring (SHM) device. Each major ship compartment would contain a SHM. In accordance with the distributed basis of SHINPADS a SHM would monitor sensors, compare the results against standards, and forward the results to a ship or machinery control room (MCR) via the data bus. Results would be forwarded as a formatted summary on a routine basis or as alerts when alarm conditions had been detected.

It is suggested that parameters to be measured would include temperature, pressure, vibration levels, particle presence, etc. as suggested in an earlier paper on machinery health monitoring (8). The SHM is seen as a microcomputer implementation of the machinery health monitor suggested by earlier research work (9). Set points or comparison standards would be downloaded from the MCR via the SHINPADS bus.

In compartments containing large equipments such as a main engine more than one SHM might be required and furthermore desirable from a distribution point of view. Such distribution of intelligence decreases the data communications since communication has been reduced to periodic summary reporting and high level alert communications.

## LOCAL CONTROL

Distribution of intelligence not only permits remote sensing and summary reporting but also supports the idea of remote or local control. The local control and monitoring module (LCMM) shown in Figure 4 not only carries out the functions of a SHM but also provides the command signals necessary for control of the device(s) being monitored.

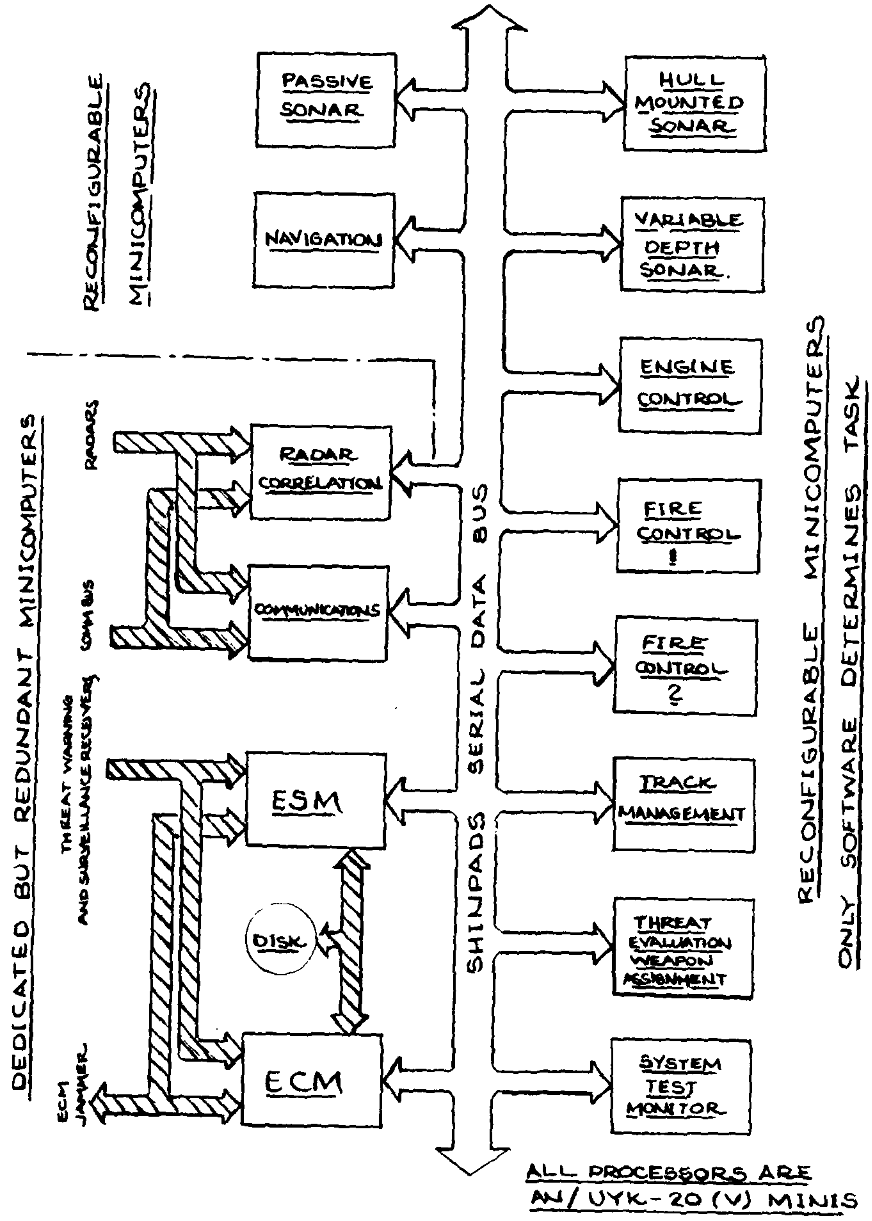


Figure 2. SHINPADS Processing System Architecture

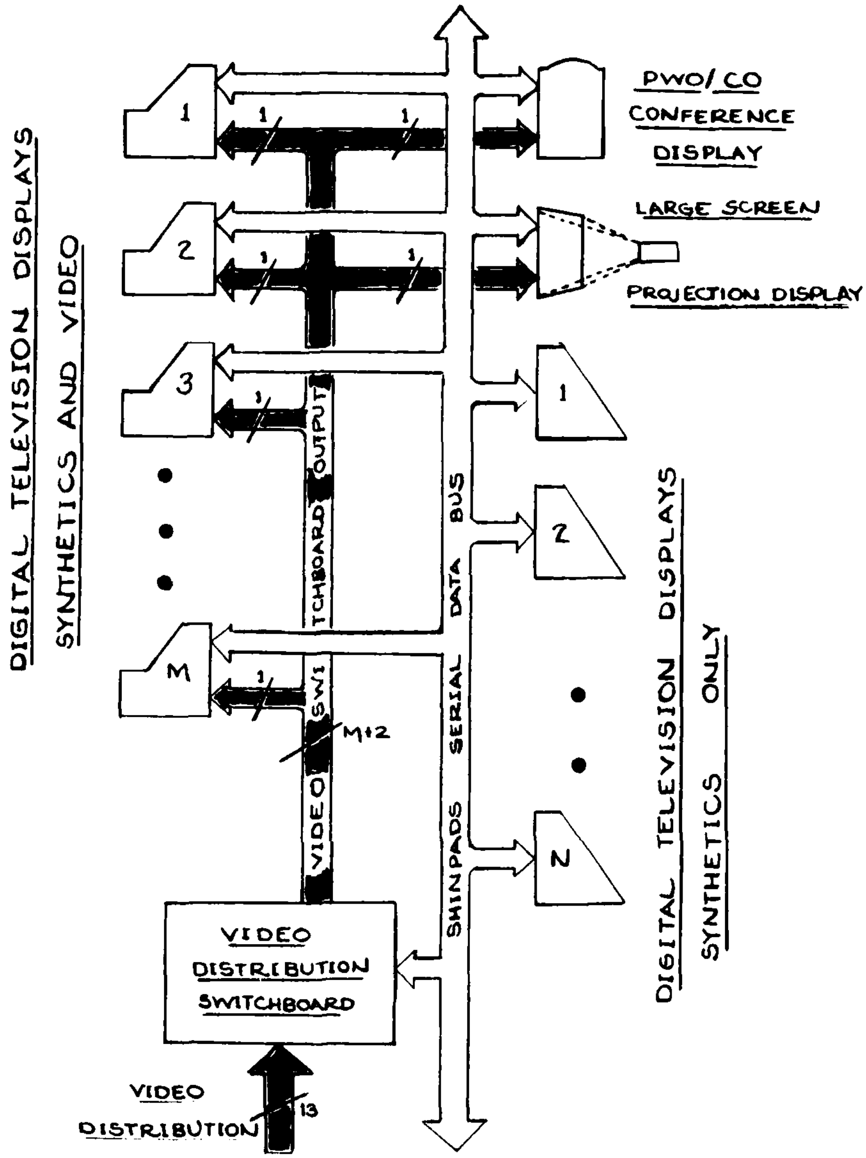


Figure 3. SHINPADS Display System Architecture

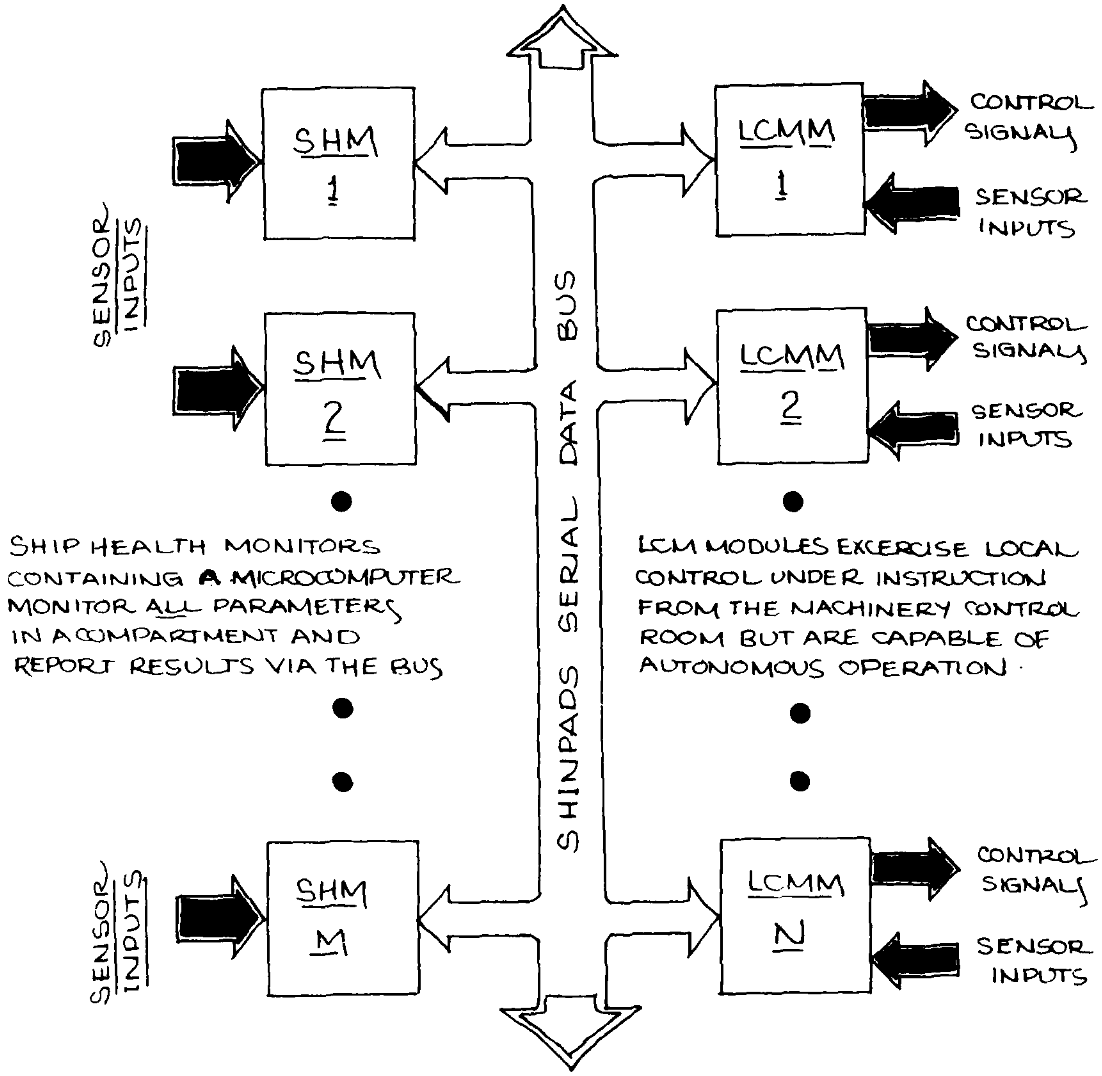


Figure 4. Local Control and Data Gathering

Such an LCMM is seen capable of running a control loop based on locally derived information and acting on command to alter the control loop. Thus in the case of a controllable pitch propellor/gas turbine shaftline the LCMM would be capable of executing a predefined control program in order to optimize fuel consumption. However in certain instances such as when involved in ASW operations the optimization conditions might change. In this case it would probably be desirable to minimize radiated underwater noise at the expense of increased fuel consumption. The new optimization algorithm would be downloaded to the LCMM via the SHINPADS data bus.

OVERALL CONTROL

The main human interface with the ship control system will be through the machinery control room. The MCR is to the ship marine and power generating systems what the operations room (or CIC) is to combat systems. As such it must provide the necessary display of information such that the operators can monitor the ships equipment status, call upon decision making tools to aid in an assessment of the status, and effect the control necessary to change the status. Upon examination it is difficult to perceive any real difference in these MCR functions from operations room functions. It is suggested that there are more similarities than generally admitted and far more similarities than present equipment differences justify. The large panels of meters, levers, and gauges appear to offer few advantages over an electronic representation which could be provided on a CRT. Electronic buttons can be drawn on the CRT face, as can MIMIC diagrams or detailed drawings, with one form being changed to the other in a fraction of a second. Storage can also be more profitable accomplished by electronic means with redundant ship's disks acting as the prime means of bulk storage and cartridge magnetic tape units providing a medium sized transportable storage means. In the rare instances where hard copy is required standardized printer/plotters can provide tabular listings, diagrams, or other graphic formats. Although bell loggers may be traditional perhaps it might be said that a graph summarizing trends is worth 1000 logged values.

Although machinery control has been stressed there is no reason why combat system equipment conditions couldn't be monitored from the same space. Should some disaster befall the MCR the SHINPADS concept provides the capability for monitoring and control to be carried out from the bridge, operations room, etc. In a similar manner, although it may be the anathema of any operations or combat systems officer, the reverse is also true.

SUMMARY

The SHINPADS concept offers reduced life cycle costs through shipwide standardization resulting in equipment, spares, documentation, and training commonality. When such standardization is coupled with the distributed architecture which removes vital links and a data bus which provides a replicated/multiply redundant interconnections a quantum jump in a ship damage resistance can be predicted. It is suggested that such cost savings, reliability, and survivability are not otherwise achievable.

The key word in this concept is synergism or in the vernacular "getting it altogether". Anything less than total ship integration is somewhat less than integration. It is proposed that the SHINPADS concept provides true ship integration.

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* Internal position papers available on request to qualified authorities.

MANPOWER REQUIREMENTS IN SYSTEMS ACQUISITION

Lieutenant Commander James K. Ruland, USN

To: Ship Control Systems Symposium; David Taylor Naval Ship R&D Center, Annapolis, 30 October 1978

> "Our main strength in maintaining the ability to guarantee our use of the sea has always been, and will continue to be highly trained versatile professionals who maintain and operate the most modern and sophisticated ships and aircraft in the world."

-- Admiral J. L. Holloway III, Chief of Naval Operations, on the occasion of the Navy's 200th Birthday.

As we continually reassess the threat and exploit the opportunities new technology opens to us, we shall surely equip ourselves with more expensive and complex military equipment. Sufficient numbers of highly trained personnel will be essential to man, maintain and support these complex systems, and it is almost inevitable that the operating and support costs will keep pace with burgeoning acquisition costs. Population trends and increased competition from other employers, however, will place severe restrictions on the quantity and quality of persons available to man the military force of the 1980s and 1990s.

This paper will summarize the manpower, personnel, and training problems facing Navy today, identify their root causes, and outline the actions that must be taken to ensure delivery of supportable systems to the Fleet of the future.

In order for the Navy to maintain a force of 460,000 enlisted personnel, 100,000 new people must enter initial training pipelines each year. High attrition rates and higher skill requirements place an increased load on the Navy training establishment to produce needed skills in the numbers required. The Navy presently has 90 ratings and over 1,000 Navy Enlisted Classifications (specialty codes). Over 21% of all enlisted personnel are presently in school, and this percentage rises each year. Personnel spend an increasingly greater portion of their obligated service in school and less and less time in the Fleet. The training to equip personnel with the skills required to operate and maintain sophisticated equipment is so extensive that it also equips them with skills which are readily marketable in the private sector.

Many of these problems can be traced directly to the system acquisition process wherein adequate manpower and training considerations were not made in the early design stages of program development. The requirement for technological superiority of weapon systems leads to pushing technology to its limits, which often overrides considerations of human capability. In attempting to achieve additional marginal capability, the manpower implications are usually ignored.

what to do after the system has been designed then becomes the problem.

This point is illustrated in the case of the sophisticated and complex automated systems on board the Navy's newest amphibious ship, the LHA. The Automated Propulsion Control System (APS) has been determined to be overly sophisticated and more difficult to maintain than estimated. As a result, the ability to provide highly qualified trained specialists was misjudged. The solution recommended is to deautomate various system components which inturn will make the propulsion system easier to maintain. The Automated Assault System (AAS) was overly complex and required an inordinate amount of maintenance. The solution recommended is to partially disable the automatic mode and to establish an assault division to maintain and operate this system. These actions resulted in a requirement for additional personnel to operate the systems in a manual or semi-automatic mode. In these cases, automation did not achieve its intended goal of manpower reduction. During source selection, the contractor estimated a total of 502 personnel. By the time the ship reached the Fleet, the number had grown to 891. The cost impact of the growth of almost 400 personnel per ship per year has been enormous; not to mention the unplanned impact on Navy°s manpower and training resources.

The DD-963 early manpower requirements were reasonable, at the time they were made. However, required capabilities added during the ship°s development, resulted in a requirement to increase bunk space in order to berth required personnel. It must be concluded that the Navy must consider areas of major manpower impact when making decisions relating to additional mission capabilities for existing platforms.

The Navy has had hardware development programs where manpower was adequately considered. Even though the Navy occasionally exhibits adequate manpower and training planning and management on an individual program basis, little has been done to identify aggregate requirements or to assess supportability of manpower and training demands.

To complicate things further, the national labor pool of 17-21 year old males (the source of new personnel) is diminishing. By 1992, it is projected that this population will be 20-25% smaller than its present size. This will produce an environment of severe competition among the Armed Services and industry for the dwindling resource.

The projected population decline has caused the Navy to focus initially on reductions of quantitative requirements almost exclusively. This "low numbers are good, high numbers are bad" approach has yielded systems that require fewer but more highly skilled personnel. As skill level requirements increase, the ratio of petty officers to total enlisted increases. Current Fleet needs identify a requirement for approximately 67% of the force to be petty officers. A peek into the acquisition hopper reveals systems that will drive the Fleet average higher still. For example the Trident Submarine is 87% petty officer intensive; while the AEGIS weapons system requires over 90%. The general trend depicted in Figure 1 would lead to a force requiring nearly everyone to be a petty officer. Thus, the pyramidal structure commonly associated with a closed personnel system is distorted, indeed inverted, yielding a personnel requirements plan that cannot be executed.

This then describes the setting which prompted the Chief of Naval Operations to task the Deputy CNO for Manpower to "develop a plan to manage and control manpower requirements growth". The Military Manpower versus Hardware Procurement (HARDMAN) Study responded to this tasking. The study analyzed the capability of the Navy's manpower personnel, and training support process to interact effectively with the Weapons System Acquisition Process (WSAP), the institutionalized forum in which all man, machine and capital labor trade offs must occur. Major study tasks were:

Task 1 Analyze current manpower/training requirements determinations, reporting and review activities as applied to the Weapons System Acquisition Process.

Task 2 Develop a new or modified structure which integrates manpower/training considerations into the weapons system acquisition decision-making process.

Task 3 Develop alternative implementation plans and conduct marginal resource requirements analyses to assess impact on existing Navy organization.

Task 4 Incorporate the results of Tasks 1, 2 and 3 into a final report to include a recommended plan of implementation of a new or modified or more rigidly enforced manpower/training analysis and review process.

One of the first steps in executing these tasks involved a determination of the scope of the Weapons System Acquisition Process with respect to the number of programs in the process. Figure 2 depicts the programs by sponsor and by Acquisition Category (ACAT). The ACAT is to a significant extent a function of the RDT&E costs and total program costs. For example, under the current criteria a major acquisition requiring at least $75M RDT&E and/or $300M total program costs is in ACAT I, whereas ACAT IV is less than $5M RDT&E and/or $20M total program cost. ACAT I programs require specific approval of the Secretary of Defense, ACAT II require approval by the secretary of the Navy and ACAT III require approval by the Chief of Naval Operations, while ACAT IV systems are approved by the Chief of Naval Material.

ACAT III and IV systems, being lower cost programs and frequently off-the-shelf items, are generally not afforded the visibility of the major systems which are subjected to the scrutiny of the DSARC review process. Even when manpower and training requirements are given due consideration, they may appear to have only minor impact when taken individually. Yet when viewed in the aggregate, the overall manpower and training impact may be staggering. Requirements of low visibility systems are frequently not felt until after they enter the fleet.

This should not be construed to mean that the major systems do not contribute to manpower and training problems. Principal Development Activities are faced with over sixty-five different instructions designed to govern the manner in which manpower and training planning must be accomplished. Program Managers, inundated with guidance and problems, recognize that their predecessors were successful either by design or default in circumventing these instructions and thus con-

sider them discretionary. Further, recognizing that "voluntary" compliance with these instructions can only place additional burden on the scarce program personnel and funds, Program Managers view the instructions as hampering the "primary objectives" of delivering the equipment on time and within acquisition cost constraints. Additionally, investment of scarce development dollars to reduce cheap outyear Military Pay Navy (MPN) dollars is not an attractive alternative to delivering the system to the Fleet on time.

The HARDMAN Study found that manpower and training requirements are not determined accurately. Every ship introduced in the Fleet in the last 20 years required an increase in billet strength of 20% or more. Additionally, in the great majority of instances, the manpower and training requirements are determined too late. As previously indicated, by the time the requirements are known it is too late to meet them. Lead times are required to enable the programming of funds in order to acquire the training resources (which take time to be developed and implemented) so that the trained personnel can be provided coincident with delivery of the equipment.

How late is "too late"? Indications are that by the time a system is ready to go from the Engineering Design Phase to Full-Scale Development, only 3% of the total Life Cycle Cost (LCC) has been expended. At this point, 85% of the future LCC expenditure has been determined. Clearly, the requirement for trade offs and key personnel-related decisions is very early in the program. If correct decisions are not made early, we will always be trying to support a design, rather than designing a supportable system.

The aforementioned deficiencies cannot be all attributed to the environment of the WSAP or attitude of the individuals who must operate within it. It is not difficult to understand that the lack of enthusiasm in manpower and training requirements determination has resulted in a paucity of good "tools" for such planning. Indeed, some of the tools used today are more harmful than productive, especially if their improper use leads to incorrect conclusions. Improper use of the NAVCOMPT Standard Pay Rates, for example, wherein all enlisted personnel are adjudged to cost approximately the same, can completely mask the impact of demands for higher skills or specific occupational groups.

Figure 3 represents a portion of the WSAP with the terminology which existed in DOD prior to issuance of OMB Circular A-109 and the DOD Instruction 5000 series. Examination of the process is useful in that most of the systems in the inventory today grew up under those rules and thresholds. Under this process, the Operational Requirement (OR) states the need for an additive capability in response to a perceived threat. The Development Proposal (DP) outlines the alternatives which can feasibly meet the need specified in the OR. From this list an alternative is selected. Then the Decision Coordination Paper (DCP) is prepared based on the selected alternative. It should be noted that for whatever reasons alternative selections are based, manpower and training implications are not included. It is only in the DCP and later that we begin to learn what we have done to ourselves. We may have, at this point, closed the door to opportunities to produce a supportable system, by virtue of the fact that; (1) we didn't take the time to look, and (2) if we had looked, and the supportability benefit resulted in a higher acquisition cost, it would have been ignored. Some tend to get too concerned with affordability, and forget about availability. It really doesn't matter how much a

second class fiber optics technician costs if none are available.

The HARDMAN study report was published on 26 Oct 1977 and in addition to highlighting the deficiencies described above, made specific recommendations for bringing the manpower and training requirements problem within the WSAP under control.

HARDMAN proposes a series of insertion points, or gates, in the WSAP (as shown in Figure 4) at which specific manpower and training information would be required. This information will permit review of the manpower and training requirements to determine their validity and supportability at each milestone review. The DCNO for Manpower (soon to be DCNO for Manpower, Personnel and Training (MP&T)), will be fully equipped to evaluate each of the alternatives with respect to manpower and training implications and present substantive findings regarding the supportability and feasibility of each alternative. This does not necessarily mean that systems which are less supportable will not be selected. There are many initiatives, such as the TRIDENT West Coast Training Facility, which may have been dropped if judged solely on its manpower merits. On occasion, overriding considerations exist which force decision makers to depart from the optimum solution. However, the decision would be made with complete awareness of the potential problems, risks and additional resources.

Figure 5 tabulates the insertion points recommended by the HARDMAN Study. It is believed that until the informational requirements for each of the insertion points is satisfied, manpower and training requirements determination will remain discretionary. In order to track the 700 to 800 systems under development, with respect to their Initial Operational Capability (IOC) dates, it is essential to acquire the information at the insertion points and determine which requirements have not been met, and if (and how) they can be met in time. At present, there is no institutionalized procedure by which the status of the manpower and training elements can be assessed.

HARDMAN intends to remedy this deficiency. In lieu of the 65 instructions mentioned earlier, HARDMAN will provide the program manager with a Plan of Action and Milestones (POA&M), which precisely details the manpower and training planning to be accomplished and when it must be done. The major concept behind the centralized authority of the program manager is as valid for manpower as it is for any other discipline. The POA&M will, therefore, be user oriented. It will provide him a discrete list of what is expected, and provide him with the analytical tools to respond. The DCNO for MP&T will use the same tools to validate the Program Manager's effort. In addition, HARDMAN will provide a supportability assessment of the system and its impact on overall Navy manpower and training resources to higher authority.

The new procedures will not be implemented overnight. It will take careful analysis and planning to develop the HARDMAN system concept. The HARDMAN development plan permits early introduction of limited HARDMAN influence concurrent with longer range developments.

The improvements sought by HARDMAN are:

- Explicit consideration of Manpower, Personnel, and Training Support (MP&TS) resource requirements in system design

- Integration of MP&TS considerations in the WSAP

- Development of needed methodology for requirements determination, life cycle costing, and tradeoff analysis

- Implementation of a capability to assess the supportability of emerging systems before acquisition decisions are made

As indicated earlier, HARDMAN will be user oriented, where the user is the Program Manager and his organizational support. The best approach for HARDMAN implementation is with the cooperation, interest and direct support of the people who drive the WSAP. Such a mutually supporting and comprehensive approach will go a long way toward solving the many problems we face today and result in:

- Better manpower and training requirements determination leading to supportable systems.

- Reduction of the need for higher skill levels.

- Reduction of the need for large numbers of personnel.

In sum we can no longer enjoy the luxury of assuming that our manpower and training requirements can be satisfied from inexhaustible resources at an acceptable cost. Every decision that we make has manpower and training implications and our people related cost has perhaps become the single most significant requirement on our resources. The long term investment in manpower and training associated with every new system being introduced into the fleet must be clearly defined as early as possible. The HARDMAN project is a major step toward ensuring full consideration of these critical resources.

Command signals are received from the PCC/LOP at 0.5-10 V DC levels. The EFA receives the signal, compares it to maximum and minimum levels to provide a loss of command measurement and feeds the command signal to a servo system, which through a solid state power amplifier, drives the power lever actuator at the engine. Feedback position and rate tachometer signals provide closed-loop operation of this position servo. Detection of loss of commands or excessive servo error signal will cause the throttle to be driven directly to idle. Rate circuits in the command loop limit the increase of throttle position to safe values.

Measurements of engine torque are derived from a small processor that performs and calculates developed torque look-up functions on a stored torque map for the engine. Horsepower is also calculated, and both values are transmitted to the LOP/PCC for use and display. The torque signal is compared to a pre-set maximum, and if the maximum is reached, an overriding signal controls the throttle control servo circuits to limit or reduce the throttle change until developed torque is below the safe value. Proper design of this loop has provided a smooth control of the throttle while limiting. By taking advantage of the torque limit control, it has been possible to also provide speed and acceleration limiting.

Over-speed protection of the power turbine is provided by reading the turbine speed with redundant sensors and shutting off the redundant fuel valves when the speed gets above the limit. These circuits are cross-connected and interlocked so any measurement of overspeed, or total lack of measurement, will shut down one or both of the two fuel shutdown valves in series in the turbine fuel line. Shutdown action is within milliseconds of the detection of overspeed.

As previously mentioned, the start/stop sequencer located in the EFA receives initiating commands from the PCC and using its logic, control and timing circuits, provides a controlled start-up or shutdown of the engine. Capability is provided by switches on the PWB's to change the time out periods for sequential control.

Emergency Manual Control Unit

In the event of damage to control system components which would make it impossible to provide normal control inputs to the engine the Navy has selected a portable manual Engine Control unit (Figure 5). It permits manual control of the fuel valves, starter and ignition, throttle position and monitors vital speed, temperature and pressure values. Because of the possibility of cable damage, the portable unit has its own cables which plug into the engine module in place of normal ship cabling. The small unit worked so well during sea trials that some observers questioned the need for the more sophisticated automatic control consoles.

Bell and Data Logging

Line printers, operating at a rate of 300 lines per minute are used to print out both bell commands and data. Although there are two printers, either can be used for bell logging. When set up to print both bell and data inputs, which would result from unavailability of one logger, bell inputs have priority.

Logger printing is done on blank paper, with headers printed each time data is printed. The printers are programmed to print each hour or on demand, and the bell logger also prints on change of EOT, change of station or change of shaft rpm or propeller pitch by five percent from normal. The data logger will print the 80 analog values of the propulsion system, plus 52 values from the Electric Plant Console and 31 values from the Auxiliary Control Console in less than 50 seconds. A typical logger is shown in Figure 6.

zero, but now the throttle is immediately commanded to the programmed control throttle position, which could initiate the auto shutdown. This self-defeating condition is controlled by processor logic which holds the command below the trigger point until shaft and engine speed are up to the required signal level. No additional hardware is required for this type of processor program.

Example 3. It is necessary to control the vent dampers and the enclosure air fans during engine operation, idle time, and fire extinguishing. If the engine is running and producing high horsepower, the fans are not to run and the dampers are to be open, but if horsepower reduces, the fans are to run. If the engine is not running and outside air temp is above 70 degrees, then fans run with dampers open, but when below 70 degrees, fans shut down, as do dampers. Since horsepower measurements are based on outputs from the torque computer in the EEA, and since the value of horsepower changes when this computer is being routinely tested, the test must be recognized in the logic to inhibit a change during the test. All these logical requirements are again handled by integrated circuits mounted on one printed wire board.

Local Manual Operation

Provision has been made to operate the propulsion plant from a Local Operating Panel (LOP) mounted near the engines in the local operating station. Originally intended to include less monitoring and control, the LOP provides total manual control of the engines and their necessary auxiliaries. As pictured in Figure 2, the LOP provides independent control of each engine and of the propeller when all control is at the LOP. Lockout switches on each engine panel remove the PCC control inputs and bypass control loops associated with the PCC. Start and stop control, enclosure fan and damper control, and throttle control are provided for each engine. In the absence of the demand display provided at the PCC, there are continuous readouts of all vital parameters, such as seawater cooling pressure, engine lube oil temp and pressure, reduction gear remote bearing pressure, fuel supply pressure, starting air pressure, engine vibration, gas generation speed, power turbine speed, intake air temperature, and power turbine inlet temperature. These displays permit an operator to operate an engine.

The Local Operating Station Instrument Panel (LOSIP) mounted directly above the LOS, provides additional instrumentation for the lube oil system in the form of scavenge temperature and filter differential pressure, and supply tank level and filter differential pressure; the fuel system inlet temperature and filter differential pressure; the throttle position; the enclosure temperature; the gas generator inlet air pressure, temperature, and discharge pressure; the power turbine inlet pressure; and the ratio between gas generator and power turbine inlet pressures.

With throttle control, pitch control and shaft brake control, the operator is able to achieve local operations, which could be required by damage to or malfunction of the PCC, or a requirement to perform off-line testing of a gas turbine.

Electronic Enclosure Assembly

The Electronic Enclosure Assembly (EEA) is an unmanned electronic assembly having the primary interface with the gas turbine. Direct interface with sensors for gas generator speed, power turbine speed, inlet air temperature and pressure, power turbine inlet temperature and pressure, fuel manifold pressure, and lube oil pressure provide data for calculations and logical decisions as well as for transmission of data to the LOP/PCC. Control of the throttle starter, igniter and fuel valves provides feed-through and override functions on console-originated commands.

A status display indicates the reason for an automatic shutdown and holds the display until reset, permitting the operator to make an initial judgment in his troubleshooting procedures.

Auto shutdown may be battle overridden, for all parameters except flameout, by the operator.

The Propulsion Control Console receives data from the gas turbine module to detect the presence of fire. If enclosure temperature gets above a preset value, or if the ultra violet detector determines the existence of flame in the enclosure, the alarm system notifies the operator. He has remote control of the Halon release mechanism to release Halon directly into the gas turbine enclosure.

Alarm Systems

Alarms in this system are derived from both analog and discrete signal inputs, and are classified as level 1 (siren) level 2 (horn) or lever 3 (bell). After an analog signal is conditioned, i.e., scaled to a 0-10 V DC level, it is compared in a designated circuit against an adjustable alarm level, and a discrete signal developed for out of tolerance conditions. This discrete will be used the same as an alarm input discrete to trigger a flashing light/circuit and energize the audible. When acknowledged, the flashing light stays on until the alarm condition is cleared and the audible is silenced. The unique feature of this system is the alarm back-up. Analog signals are also fed to the digital processor, where they are compared to the same preset level to detect out of tolerance conditions. If the designated circuit has detected the alarm, that fact is fed to the processor, and no further processor action is taken. However, if the processor detects an alarm that was not detected by the circuit, a "computer generated" alarm is initiated and the designation of the alarm is printed on the data logger. To keep such alarms from being a nuisance until repairs can be made, the computer alarm may be overridden.

Logic Circuits

The capabilities of integrated circuits are used to simplify the logic used in the system, permitting straightforward implementation of a number of necessary control and interlock circuits. A few examples are provided.

Example 1. The dynamic analysis referred to previously recognized the slow propeller pitch response resulting from reduced pressure in the gear-driven hydraulic pump when operating at reduced shaft speeds. To obtain more optimum operational response, the standby pump is started when shaft speed reduces below approximately 100 rpm and then is shut down again when the speed increases above approximately 115 rpm. Since this pump is also controlled by a loss of gear-driven pump pressure, and since the pressure sensor is located at a point in the piping where the pressure drops to minimum during switchover from standby to gear driven, it is necessary to delay the reaction to pressure drop until pressure builds back to the proper value. All this is done by a small handful of integrated circuits mounted on printed wiring boards.

Example 2. It would seem that releasing the shaft brake would be a simple thing to do. Putting the brake on does require that the engine be at idle, prop pitch near zero and shaft speed below 75 rpm. This requires a simple logic circuit, but releasing it should give no problem. However, the over-speed protection of the engine, with its redundant speed measurements, has a feature that will cause an automatic shutdown if both speed signals are lost and the throttle lever has been advanced above a 1/3 position. With shaft brake set, the speed signals are zero, but the engine is commanded to idle. When the brake is released, the speed is still

Outputs of the throttle commands go to the Electronic Enclosure Assembly (EEA) containing a power lever actuator amplifier which, in turn, drives the power lever to the desired position, depending on the input DC command and confirmed by the position feedback potentiometer in the actuator. Positioning of the pitch control valve is directed by the output driver from the LOP and feedback position is obtained from a non-linear potentiometer positioned by the pitch control hydraulic piston extension.

Start/Stop/Sequencing

To bring an engine on line, a number of pre-start permissives must be satisfied. Seawater cooling must be up to pressure and the pump discharge valve open, gear lube oil up to pressure, turning gear not engaged and its access covers closed, the shaft brake and appropriate power turbine brake not engaged, the Halon system must be ready, the enclosure fans must be energized, the fuel system up to pressure, both fuel tanks not empty and fuel supply cutoff valve open, the coast down pump must be off, and the bleed air valve must be closed. If neither engine is running, the shaft must be stopped (less than 1 rpm in 5 sec.) and the prop pitch at zero.

Automatic start is a command to the sequencer in the EEA which starts the air-driven starting motor, measures and times gas generator speed (which must be up to 1200 rpm within 20 seconds), then turns on fuel oil and ignition, and times out increase of gas generator speed (must be up to 4500 rpm within 90 seconds) and detects flame by measuring power turbine inlet temperature. If temperature is above $400^{\circ}F$ in 30 seconds, then an engine at idle signal indicates the engine is available for commands.

The above sequence can be timed manually by selecting the manual start mode. This allows the operator to extend the time out periods if it appears the proper speed and temperature conditions might be reached in a little more time.

Normal shutdown can be automatic or manual. If automatic, the engine throttle will be commanded to idle, where it will run for five minutes to allow a cool-down period and then shut off the fuel valves. Manual stop bypasses the time--the operator could run at idle for a period of time before closing the valves if the time were available. Capability is provided for testing the redundant stop valves independently during a routine manual stop.

Start and stop of an engine from the LOP can be performed if other controls are locked out from the PCC. Some of the safety features of the start/stop sequencer are bypassed in this mode and the operator must control starter, ignitor, and fuel and do his own speed observation and timing.

Safety Circuits

There are a number of safety circuits provided in the system. Flame out, low engine lube oil pressure, high gas turbine inlet temperature and high vibration levels on either the gas generator or power turbine will cause an immediate shutdown of the fuel valves at the engine. In each of these cases (except flameout) an alarm will sound before the shut-down limit is reached, allowing the operator to make more orderly adjustments of throttle settings if appropriate. Shutdown due to flameout, low lube oil press, and high T5.4 are redundant between the consoles and the EEA.

The vibration analyzer recognizes the sharply filtered once-per-revolution vibration levels of either gas generator or power turbine at either spool speed, compares the level to both alarm and shutdown levels, and commands the appropriate action.

and the Engineering Operating Station (EOS). Displays of shaft speed and propeller pitch, and a shaft brake control enable the bridge to directly control the shaft speed through throttle and prop pitch commands and set the shaft brake without concern for damage to the brake.

Control at the CCS may be taken by operation of transfer switches, providing a smooth transfer since the single lever at the propulsion control console will have tracked the bridge lever and will be commanding the computer to the same outputs as the bridge. Computer outputs for each setting are selected from a stored schedule, developed after careful simulation of dynamic responses of all ship elements. (The evolution and characteristics of these schedules are described in another paper in these Proceedings.) There are two types of throttle control in the programmed mode--constant speed and constant power. The constant speed mode requires feedback of shaft speed to close the control loops, while the constant power inputs rely on the stable performance of the LM2500 to achieve a constant power output.

There are other modes and locations from which throttle and pitch commands can be transmitted. Figure 4 shows that programmed control is available at the bridge, either programmed or remote manual at the PCC in the CCS, and local manual at the Local Operation Station (LOS).

Thus, operation of either one or both engines can be performed at any of the control locations, and by proper switch selection and control of the LOS lockout features, one engine can be controlled from one location, and one from another. The single propeller will receive pitch commands from the priority location. If either engine is in programmed control, then the propeller is also. In similar fashion, control of both engines has to be switched to the LOP in the LOS by means of both lockout controls before the pitch control is available from the LOP.

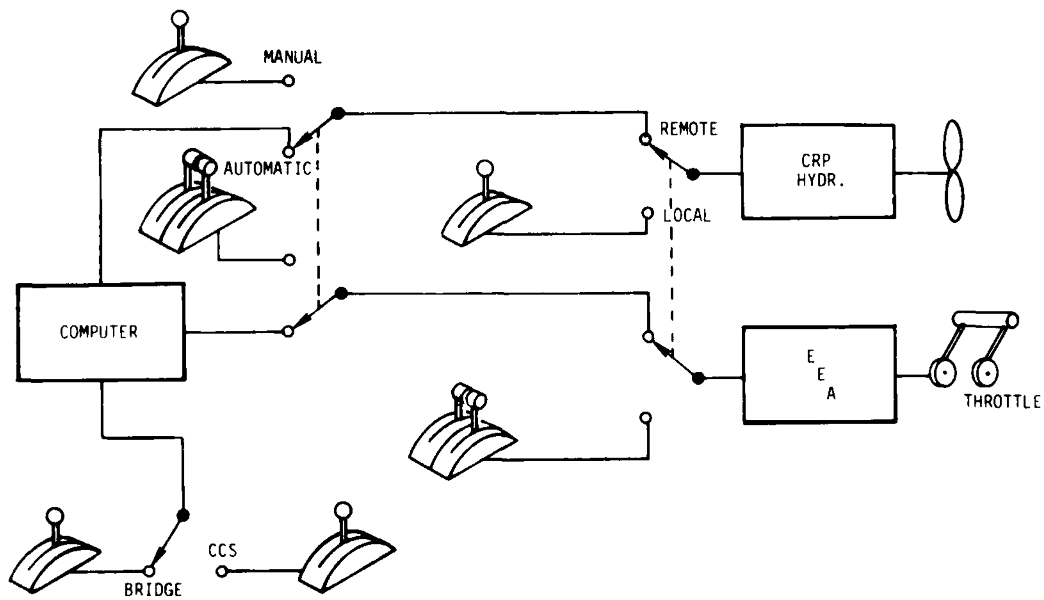


Figure 4. Control Location Capabilities

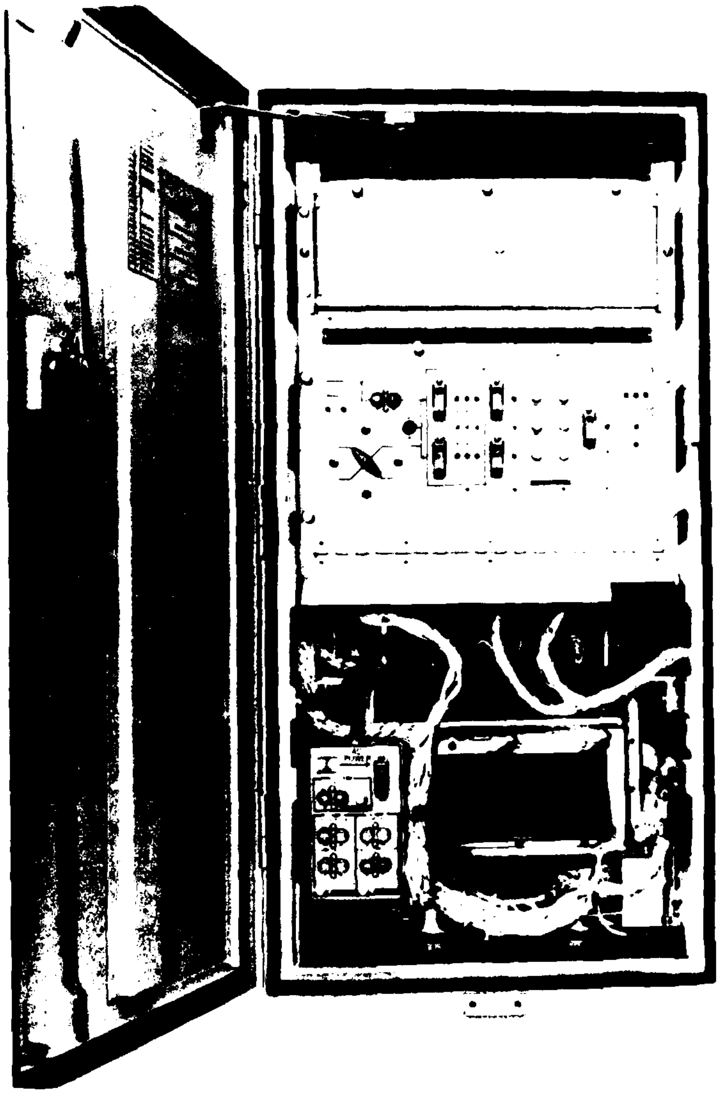

Figure 3. Electronic Enclosure Assembly

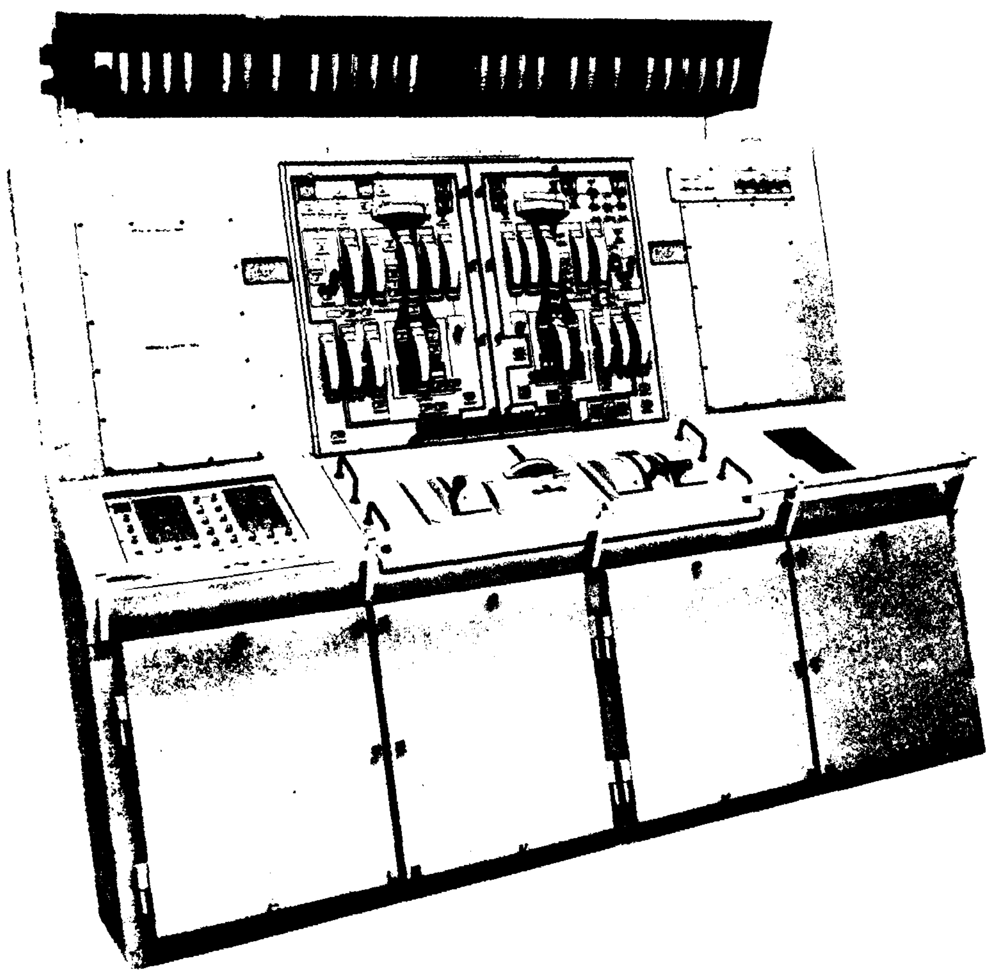

Figure 2. Local Operating Panel

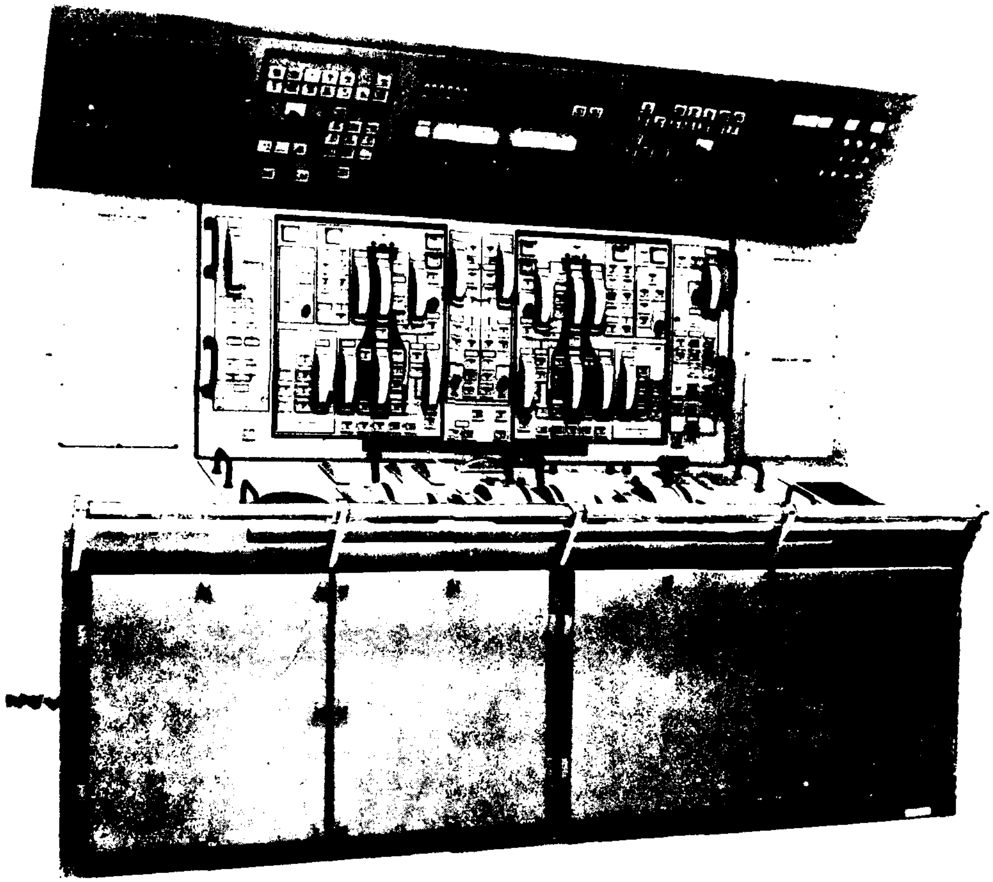

Figure 1. Propulsion Control Console

AUTOMATED MACHINERY CONTROL
FOR THE FFG-7

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INTRODUCTION

When the Oliver Hazard Perry (FFG-7) left the dock at Bath Iron Works for sea trials, the Captain had control of the propulsion plant on the bridge, using a single throttle lever. When she returned after three days of highly successful maneuvers - crash ahead, crash stop, silent running, high speed turns, one and two engine operation, single lever programmed control was established as normal for that class of ship. Few of the observers aboard realized that the electric plant had on several occasions been automatically corrected for faulty operation, with standby generator brought on-line without operator action.

The capability to provide the minimum manning and the optimized performance experienced during these trials and by the leadship crew since operational availability, is housed in the machinery control system supplied by the General Electric Company's Ground Systems Department of Daytona Beach, Florida. Providing computerized control of the two LM2500 gas turbines and the controllable, reversible pitch propeller, the propulsion control system combines human-factored control panels with digital, automatic control circuits to enable minimum manning in the Central Control Station (CCS) and to achieve routine optimized performance. On-line readiness and rapid response capabilities of the gas turbines and propeller are maximized by the computerized control system. Using the same type of controls, the electric plant is continuously monitored for malfunctions, and when its computer detects out-of-tolerance performance, it initiates appropriate corrective action to reconfigure the plant with standby generators being brought on line as needed. The auxiliary systems monitor the status, and sound alarms when an out-of-tolerance condition exists. The damage control system is monitored for fire, smoke and flooding, and the Fire Main pumps and valving controlled for fire fighting. Bell logging of propulsion changes and data logging of all critical plant parameters take place as required.

The propulsion control console (PCC) is shown in Figure 1, the Local Operating Panel (LOP) in Figure 2, and the Electronic Enclosure Assembly (EEA) in Figure 3.

The description of the propulsion control, electric plant control, auxiliary control, and damage control systems which follows will discuss some details of the equipment used for each control system and will present some of the unique design problems encountered on this ship control system resulting from the nature of the propulsions and electrical components used.

PROPULSION

Throttle and Pitch

The propulsion control loop starts at the bridge, where the single lever control can be in control of the system after a transfer sequence between the bridge

| HARDMAN Subsystem | WSAP Stage | HARDMAN Insertion/Control Point | Data Description |
|---|---|---|---|
| H1 | Concept Formulation | 1<br>2<br><br>3 | Hardware design features<br>Aggregate manpower and training estimates<br>Planning milestones |
| H2 | Concept Formulation | 4<br>5<br>6 | Annual and life cycle cost<br>Tradeoffs among alternatives<br>Planning milestones |
| H3 | Engineering Design | 7<br><br>8<br><br>9 | Manpower and training elements by skill level & sponsor<br>Tradeoffs between hardware and manpower/training<br>Updated milestones |
| H4 | Engineering Design | 10<br>11<br><br>12 | Updated Costs<br>Tradeoffs between components and manpower/training<br>Revised milestones |
| H5 | Full Scale Development | 13<br><br>14<br>15 | Manpower and training elements by skill & occupation<br>Fiscal summaries<br>Updated milestones |
| H6 | Production Deployment | 16<br>17<br>18 | Manpower and training planning actions<br>POM inputs<br>Revised milestones |

Figure 5. HARDMAN Insertion Points

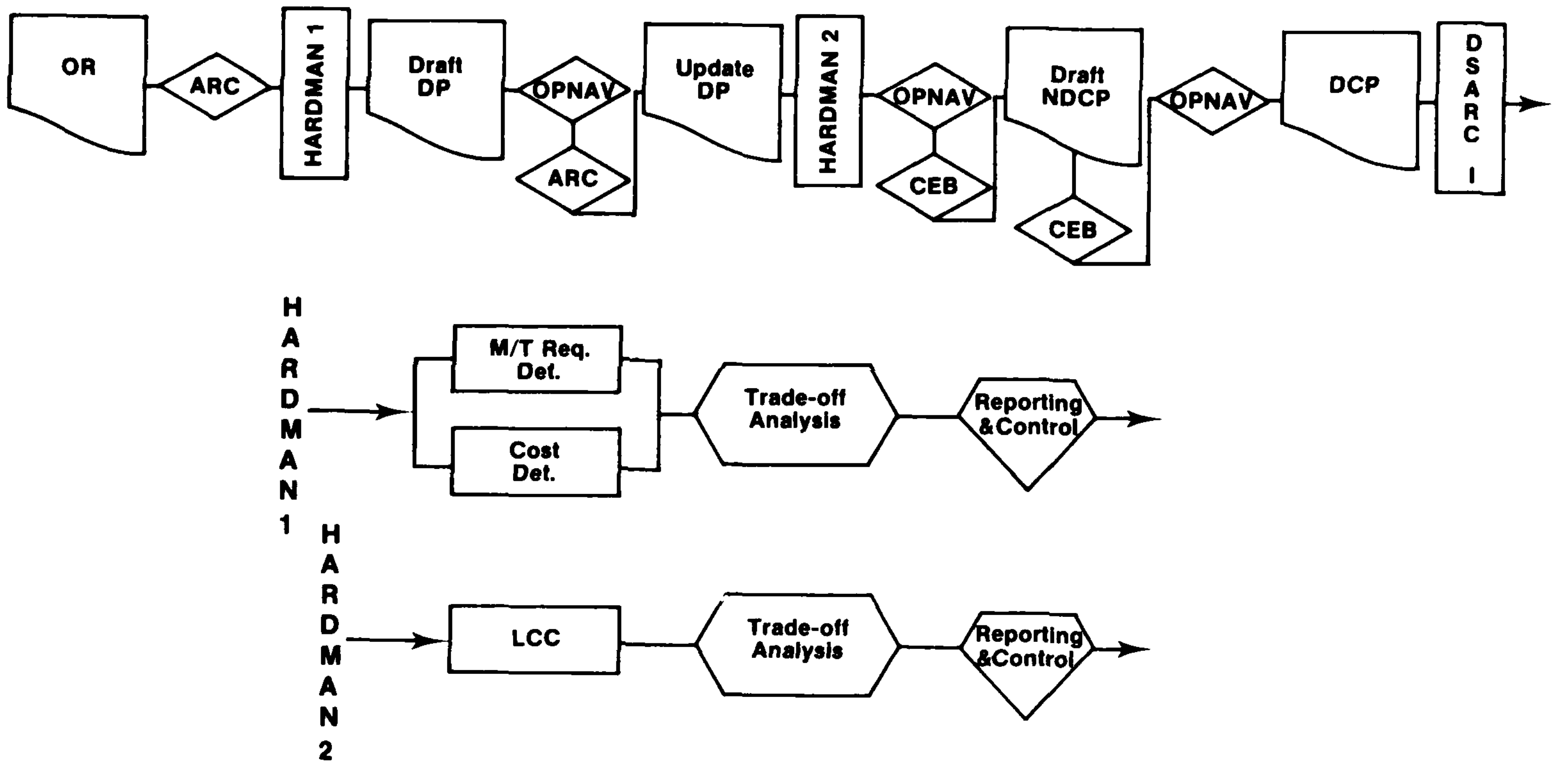
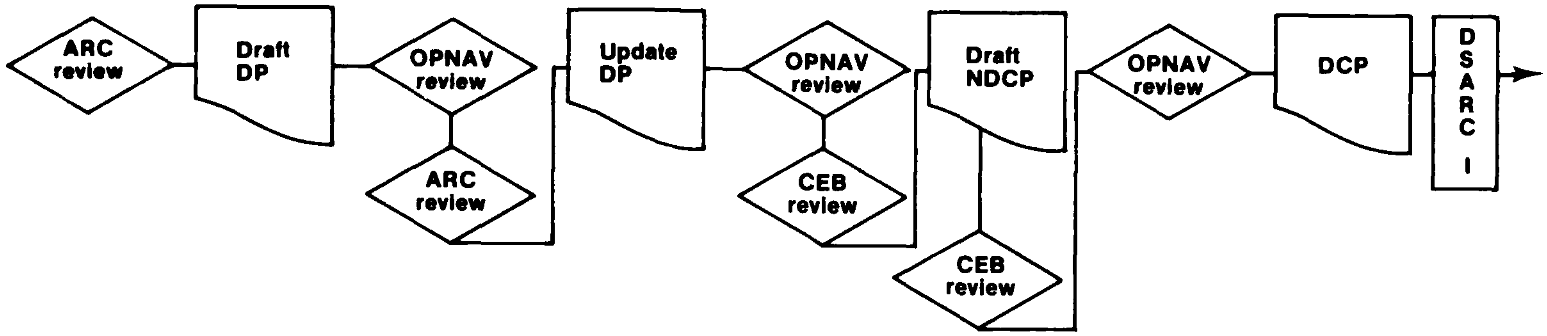



Figure 4. HARDMAN/WSAP Interface




NUMEROUS MANPOWER AND TRAINING HOLES IN PRESENT WSAP.

OPERATIONAL REQMTS GENERALLY RESULT FROM TECHNOLOGY PUSH VICE REQUIREMENT PULL. EQUIP DESIGN OFTEN DETERMINED BEFORE OR IS WRITTEN.

DEVELOPMENT PROPOSALS SELDOM CONTAIN MANPOWER/TRAINING PROFILE FOR EACH ALTERNATIVE THEREFORE THEY ARE VIRTUALLY NEVER CONSIDERED IN SELECTING PROGRAM ALTERNATIVES.

DECISION COORDINATING PAPERS ARE NOT FORMATED TO ACCOMMODATE MANPOWER INFO.

DCP BECOMES OPERATING AND POLICY GUIDANCE DOCUMENT FOR BALANCE OF ACQUISITION BUT MANPOWER REQUESTS ARE GIVEN LITTLE IF ANY IN DEPTH CONSIDERATION.

NEED CHECK POINTS/RESOURCES/TOOLS TO ADEQUATELY ASSESS MANPOWER IMPACTS.

Figure 3. WSAP Concept Formulation Phase

| Acquisition Category (ACAT) | OPNAV | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 01 | 02 | 03 | 04 | 05 | 06 | 09 | 94 | 95 | 98 | 99 | |
| I (RDT&E > $75M or Production Cost > $300M) | - | 1 | 26 | - | 30 | - | - | 5 | 6 | - | - | 68 |
| II (RDT&E > $20 M or Production Cost > $50M) | - | 33 | 85 | 2 | 45 | - | 2 | 18 | 13 | 7 | - | 205 |
| III (RDT&E > $5M or Production Cost > $20M) | 2 | 28 | 57 | 10 | 79 | 1 | 7 | 49 | 12 | 43 | 5 | 293 |
| IV (All Other Programs) | - | 5 | 19 | 12 | 36 | - | 4 | 26 | 4 | 11 | 13 | 130 |
| Total | 2 | 67 | 187 | 24 | 190 | 1 | 13 | 98 | 35 | 61 | 18 | 696* |

*Current Total May Be In Excess of 800-900 Programs

Figure 2. Number of Projects by ACAT and OPNAV Sponsor

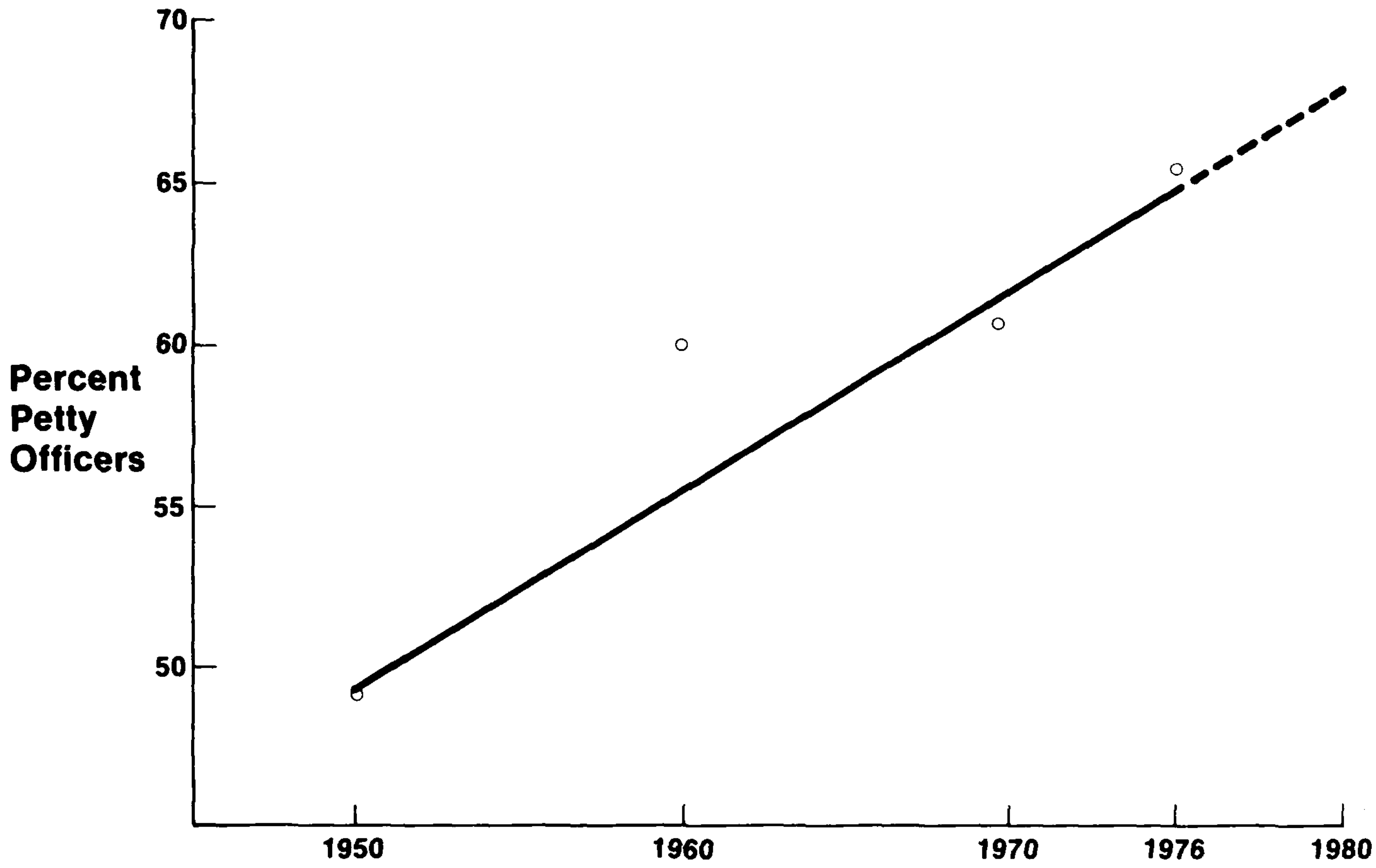



Figure 1. Petty Officer Requirements Growth

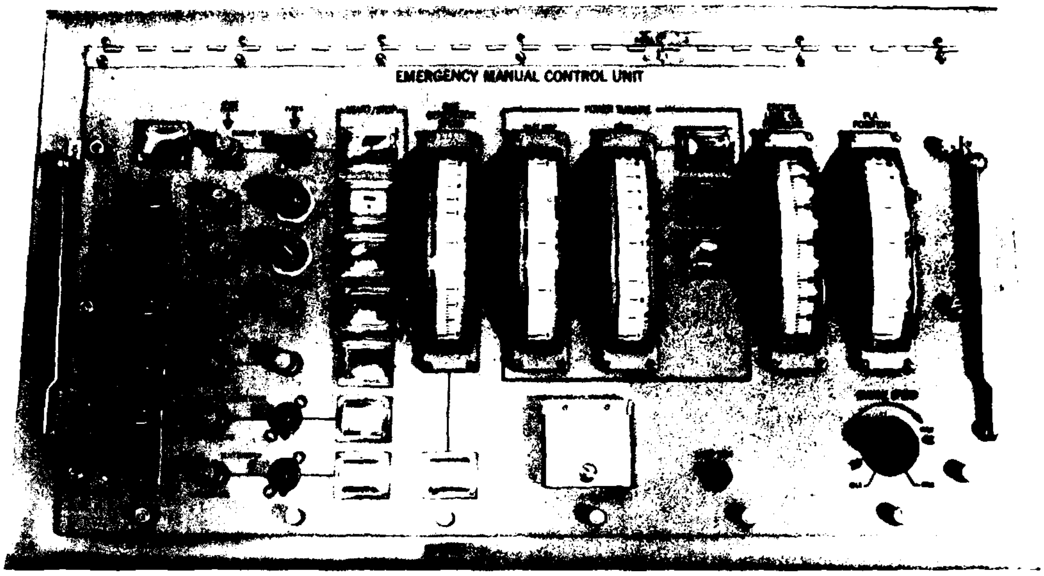



Figure 5. Emergency Manual Control Unit

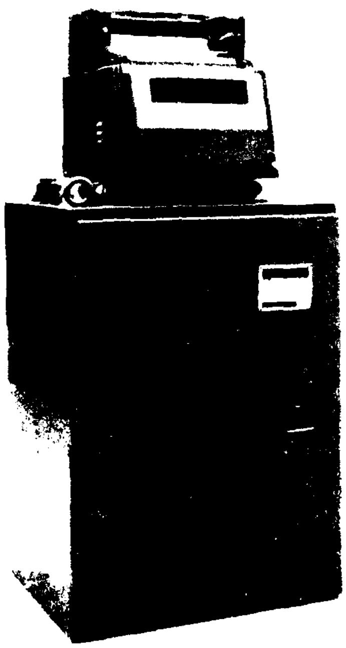


Figure 6. Typical Bell and Data Logger

## Power Supply Enclosure

To supply a well regulated and isolated source of DC power to various system components, a power supply enclosure is provided. Shown in Figure 7, it derives its inputs from the ships uninterrupted power supply, which has 15 minutes of battery back-up, and converts and regulates +28, +5, and $\pm15$ volts for each FFA and a separate +28 V supply for a number of motors and valves in the propulsion control system auxiliaries. All DC power supplies are redundant, diode coupled regulators, with each supply in a redundant pair capable of supplying the total connected load. As in other consoles, a monitor of each supply, ahead of the coupling diode, reports the condition of each supply to the operator by way of panel-mounted lights.

# ELECTRIC PLANT CONTROL

## Electric Plant Control Console (EPCC)

The Electric Plant Control Console shown in Figure 8 is located in the central control station face to face with the Propulsion Control Console. Because of its compatible alarm system and its automatic supervisory control system, normally it can be under the control of the same operator performing watch over the PCS and the Auxiliary Control Console. However, its functions do provide for full manual control, which the operator can elect to perform at his choice.

## SSDG Control

The four 1000kw Ships Service Deisel Generators (SSDG) are each connected to a switchboard through a generator circuit breaker (CB), and the four switchboards are connected in a ring-bus configuration by eight bus-tie circuit breakers. Control of each of these breakers is exercised from the console by a system of manual CB control switches, CB control circuit selector switches, and parallel relay controls.

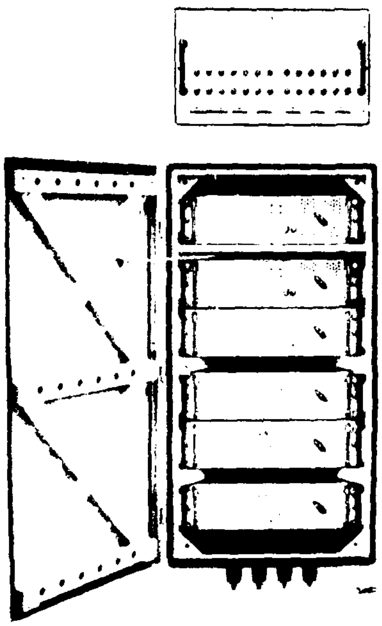


Figure 7. Power Supply Enclosure

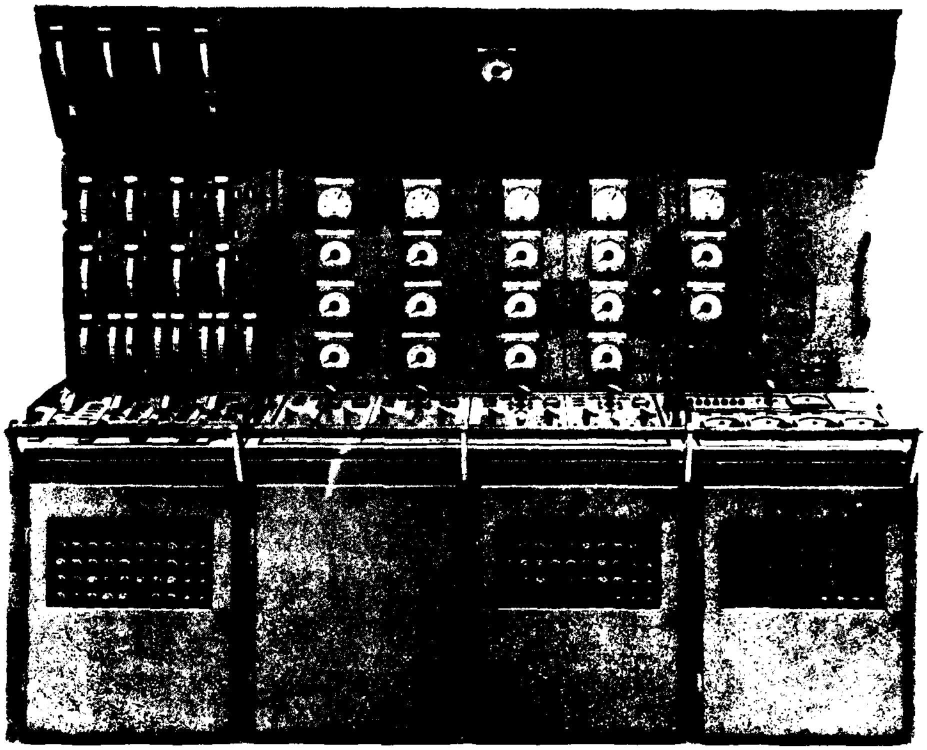


Figure 8. Electric Plant Control Console

The circuit breakers rely on their own source for control power, with the bus-tie breakers having a voltage sensitive relay to connect the control circuit to either the switchboard bus or to the connecting bus for control power. This can create problems when neither bus is energized.

The console connections to the uninterrupted 115 V supply are used for control power to trip a breaker, ensuring capability to open the breaker under any bus configuration.

Figure 9 is a simplified circuit diagram depicting the circuit breaker controls.

Note the possibility of a sneak circuit when using the paralleled relays to close a CB, and the interlock in the control line to prevent more than one CB from being closed at the same time.

The generators are provided with governors which can be remotely controlled from the console. This is an operator function and is accomplished by an increase/decrease switch for each generator to change the frequency. The operator can also manually change the governor modes by putting them in droop or isochronous.

Voltage regulators at each generator can be remotely controlled by a panel mounted raise/lower switch. The differential and droop modes of the voltage regulators may also be operator selected.

Each SSDG is equipped with a remote operated start/stop controller, and an automatic paralleling device (APD) is mounted in each switchboard to monitor voltage level, frequency, and phase angle, provide control inputs to the governor and voltage regulator, and then close a CB permissive contact. This APD is controlled either manually or automatically from the EPCC, and its output contact may be

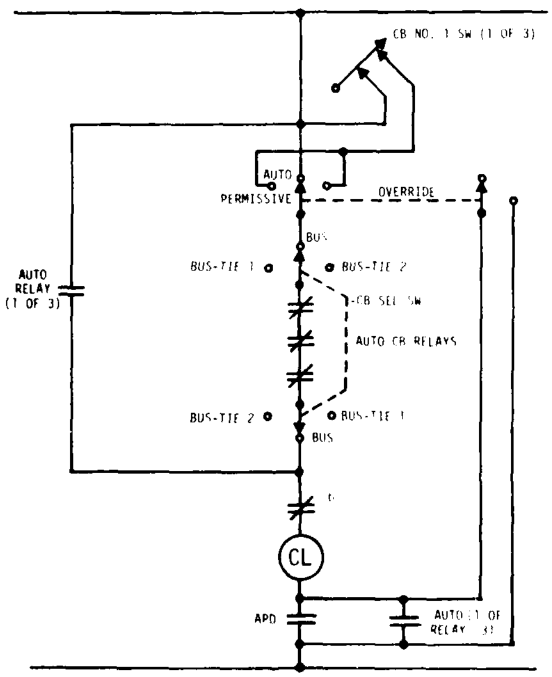



Figure 9. Circuit Breaker Close Control

bypassed by a spring-loaded switch when the operator is paralleling across a circuit breaker by using the synchroscope or lights.

The switchboards are equipped with local/remote switches which disconnect the console inputs, except for switchboard 4 which is in the Central Control Station and for which the console provides local control. Each switchboard has a reverse current relay for opening the generator CB and a load shedding device for disconnecting non-vital loads in the event of generator overload. Shore power circuit breakers can be tripped from the console.

Monitoring

The console provides the function of a centralized monitor for the electric plant configuration and the health of its many components. Measurements of the temperature of each phase of the generators is read on a panel meter. Also, the temperature of each of the 16 diesel cylinders is measured and alarmed and is selected for panel display on four meters. The combined exhaust temperature of the diesels is measured and is available for demand display.

Fuel tank levels are measured and alarmed, and suction valve open/close control provided. Fuel manifold pressure is measured and alarmed, and fuel return temperature is measured and alarmed. An alarm is also provided for the acoustic cell fire warning.

Diesel prime mover speed is measured and displayed and an automatic trip alarm is provided. The alarm is generated either by an external trip signal or by the command from the supervisory control to shut down an SSDG. Lube oil supply and pump discharge pressure are measured and alarmed and the supply pressure is compared to a set point for automatic shutdown. Jacket water temperature is measured and alarmed, and the seawater suction and overboard valves are provided with open and close controls.

Monitoring of generator and bus outputs is performed in two ways. In addition to the normal panel display of generator voltage, current, frequency, and power, of bus voltage and frequency, and of bus transfer current, the console is equipped with transducers which measure voltage, current, frequency, watts and vars, translate them into equivalent 0-10 volt analog signals and transmit them to the processor for display and supervisory system calculations.

The status of 64 vital load circuit breakers is displayed, although no control is provided.

Supervisory Control

In addition to the manual controls provided, the FPCC has the task of continually monitoring the status of the connected system, determining if out-of-tolerance conditions exist, and correcting the plant for continued operation. To perform its function the supervisory control processor needs to be supplied with the following signals (number of signals): Circuit breaker open/close (12), generator voltage (4), generator frequency (4), generator current (4), generator kilowatts (4), generator kilovars (4), bus voltage (4), fail to start (4), manual start (4), engine lube oil pressure (4), engine RPM (4), jacket water flow alarm (4), local/remote control status (3), governor mode (4), voltage regulator mode (4), governor mode select switch position (4), generator excitation (4), generator excitation limit (4), generator excitation limit time delay (4), shore power connections (7), load shedding (1), synchronizing equipment energized (4), and generator set up for auto (4).

Using the measurement of voltage on the generators and the bus, and the status of the circuit breakers, the supervisory processor can establish the plant configuration. This can be full plant, split plant and any combination of the four

generators in either or both of these configurations. Thus, there is a wide variety of configurations for the plant and the effect of the fault and the corrective action will be different for each of them.

The different malfunctions which are monitored and for which corrective action is required are classified and ranked in importance.

Class I: These are severe malfunctions which require instantaneous corrective action to keep from losing the electric plant, and they can occur on a SSDG 1 in parallel, single or oncoming mode of operation. The faults are:

1. Lubricating oil pressure too low
2. No fresh water flow
3. Automatic trip of the generator circuit breaker
4. High excitation current
5. Overvoltage

Class II: This fault can occur on a single SSDG either running or oncoming.

1. Over speed (high frequency)

Class III: These are bus faults and are due to governor or regulator problems. They can occur with a single generator on line or with parallel generators.

1. Under voltage
2. Under frequency

Class IV: These faults are measured at the generator when more than one generator is running in parallel. They are the result of governor or regulator faults:

1. Peal load unbalance
2. Reactive load unbalance
3. Real load oscillation

Before the supervisory processor can operate, some initial conditions must be satisfied. At least one spare SSDG must be set up for automatic operation. Its starter must be prepared to accept a remote signal, the lube oil pump must have its valves open, the switchboard must be in remote, the voltage regulator must be in automatic, and the console starter select must be in automatic. The circuit breaker select switch must be in the bus position (the supervisory cannot synchronize across a bus-tie circuit breaker), the supervisory mode switch must be in automatic, and the APD mode switch must be in automatic.

The processor which provides the supervisory controls, samples data and makes decisions each time it cycles, which is about every 200 miliseconds. Thus, each reading is updated five times a second. Sampling of the data, and corrective action is done by looking at class I faults first and if there are none proceeding to class II, and similarly to class III and IV.

If a class I fault is detected, the first decision is whether the generator is on-line or oncoming. Either way, the faulty generator is tripped. If the generator is oncoming and no other standby is available the operator is alerted through the trip alarm and no standby generator available alarm. If another standby is available, it will be started. If that generator's switchboard bus is dead, but the rest of the plant is live, the proper bus-tie breaker will be closed. (The processor will not close a bus-tie breaker between two buses if there is voltage on both of them). The mode of oncoming generators governor will be made the same as the rest of

the plant, and then the automatic paralleling device will be initiated and a generator circuit breaker close command given. When the APD achieves synchronization the circuit breaker will close and the system will be reconfigured.

If the oncoming generator's bus was dead, and the plant was dead, then the generator circuit breaker would be closed on the dead bus. Remember the 15 minute battery back-up on the control power system. The controls described above are not initiated until the oncoming generator reaches about 90 percent frequency and 70 percent voltage.

If the oncoming generators bus had been live, indicating a bus-connected live plant, the control logic would merely put the governor in the correct mode, and then initiate APD action and close the generator CB as described above.

(A simplified flow chart illustrating this action is shown in Figure 10.)

The above description was for the case in which the detected malfunction was on an oncoming machine. Let us now consider a machine already running. If running in parallel, the first step is to trip the SSDG, which opens its circuit breaker. Again, if no standby is available, the operator will be alerted. If a machine is available, it will be started, brought up to speed and voltage and treated with the same logic outlined in Figure 10.

If the fault had occurred on a machine that was single running, after the faulty unit was tripped, that particular bus would be dead. If the plant had been split and another machine is available, then the logic of Figure 10 would apply. Note that the bus-ties would be closed, eliminating the split plant, before the new

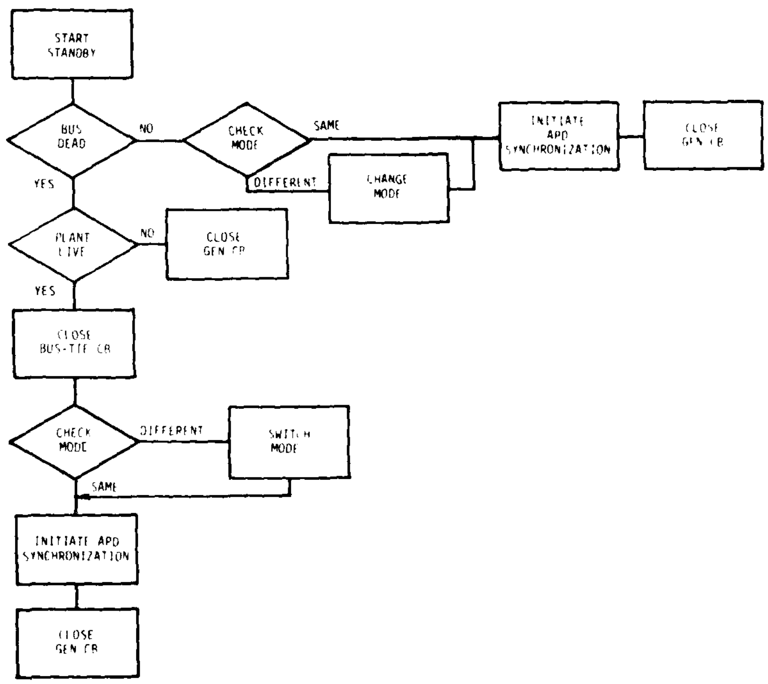



Figure 10. Logic for Connecting Oncoming Generator

unit is paralleled. Remember that the supervisory processor cannot parallel across a bus-tie breaker. If the faulty unit had been the only one running, the plant would be dead while the standby was coming up. The generator circuit breaker would be closed onto its dead bus and then any bus-tie breakers open would be closed.

Some of the supervisory control programming problems which had to be addressed concerned the start-up timing. For example, the lube oil pressure raised so slowly and the processor looked at data so rapidly that a lube oil failure alarm caused shutdown of an oncoming engine, which had no faults, until the proper delays were built into the program. The voltage rise curve was important, and the response time of bus-tie relays (including the search for live control voltage) requires that bus-tie circuit breaker commands be held for several seconds.

It is an impressive sight to see the action just described take place aboard ship. The ship builder and its design agent are to be congratulated for defining and integrating a system which works so well.

When the processor determines that no class I or II fault exists, it next looks for class III and IV faults.

Before describing the corrective action for class III and IV faults, let us review the measurement of faults.

1. Low lube oil pressure--If the pressure measurement is below approximately 40 psi seven seconds after an engine reaches 90 percent of synchronous speed or any time thereafter, then it is considered a lube oil failure. This comparison is made in the processor.

2. No fresh water flow--This is a contact closure signal from the fresh water flow switch at the diesel cooling jacket, and is changed to a discrete logic level and input to the processor.

3. Generator tripped automatically--This again is determined from a contact closure at the generator circuit breaker, and is input to the processor.

4. High excitation current--This analog measurement, which can be read on a demand display, is amplified from the 0-50 MV reading taken across a field current shunt to the usual 0-10 V signal required for A-to-D conversion and then input to the processor. The alarm comparison level is also fed into the processor from an operational adjustment panel, where a selection of values up to 150 amps can be made. Since the circuits react so rapidly to changes, a time delay adjustment is also available. Therefore, if the field current value stays above the shutdown level for an adjustable period of 0-10 seconds, corrective action starts.

5. Overvoltage--Generator voltage is read into the console from instrument transformers located in the switchboard. In the console they are converted to DC analogs and input to the processor. The the reading is compared to a set point of approximately 550 volts, ıd if higher, will initiate corrective action.

6. Diesel overspeeding--Prime mover speed is measured by a magnetic pickup, and the frequency signal converted to a DC analog value in the console. The processor checks this value and if the speed is 10 percent high for 200 milliseconds, then corrective action is initiated.

7. Undervoltage--This alarm is for bus voltage which is read into the processor by the same technique used for generator voltage. If there is only one generator on the line there is no corrective action, although an alarm is sounded to alert the operator.

8. Underfrequency--The frequncy of bus voltage is converted to a DC analog by the transducers in the console. The processor compares to a set value of 56 Hz and takes corrective action when the input is under that value for 5 seconds.

9. Real load unbalance--Wattmeter type transducers convert the three-phase voltage and current readings to a DC analog and feed the data to the processor. There the readings of each generator are compared to each other and if the difference exceeds an adjustable value of 0-125 kW for a period of 0-10 seconds, the processor initiates corrective action.

10. Reactive load unbalance--This reading is made in a fashion similar to real load unbalance, except the console-mounted transducers measure vars instead of watts.

11. Real load oscillation--This measurement is made from power values already in the processor (see 9 above). Calculations are made of the average power for the number of generators on line, and the value of each generator's power compared to the average. If any value is alternately above and below the average by an adjustable 0-50 kw value for up to 10 seconds, it is an indication of governor problems and corrective action is initiated.

Returning to the description of class III and class IV faults, a description of the logic involved upon detection of a fault is in order. For any bus there can be one or more generators feeding it, so the first decision is just that. We will examine the first case where only one generator is on the bus. If no other generator is on line then we have a potential dark ship and thus the need to start a standby--if available. If none, the operator is alerted. If a standby is available it will be started, and its bus isolated by opening bus ties. As soon as the standby is up to speed and voltage, its generator CB is closed, putting power on that bus.

Now the faulty unit is tripped, and its bus will be isolated. The remaining switchboards, which are now dark, are then connected to the line bus powered by the new generator. When the faulty unit is off line, as determined by an open generator CB, its bus-ties are now closed and the new unit is carrying the plant. A simplified logic diagram is shown in Figure 11.

If another generator had been on the line in the above case, it would have signified a split plant operation. Remember the defective bus was determined to be fed by only one generator. If the plant was split, the faulty generator is immediately tripped and its bus isolated. The other bus-ties are then closed, restoring all but the defective bus. Now a standby is started, when up to speed and voltage it is synchronized with its bus, and upon faulty generator CB open, all bus-ties are closed.

The other alternative mentioned earlier was that if there were two or more generators on the faulty bus. When that is the situation, the corrective action is different, for it may be possible to keep the generator on line. If the governors have been operated in droop, then the bus-ties will be opened in a combination that will split the plant, and leave all buses energized but from only one generator. This should eliminate all class IV faults, since at least two generators are required for such a fault. If the class III fault still exists, then the corrective action follows the description given above bus on a single generator case (See Figure 11).

If the governors are operated in isochronous, which would be the usual case, the processor first changes to droop and then waits 20 seconds to see if a fault still exists. If it does the next step is to split the plant. If a fault no longer

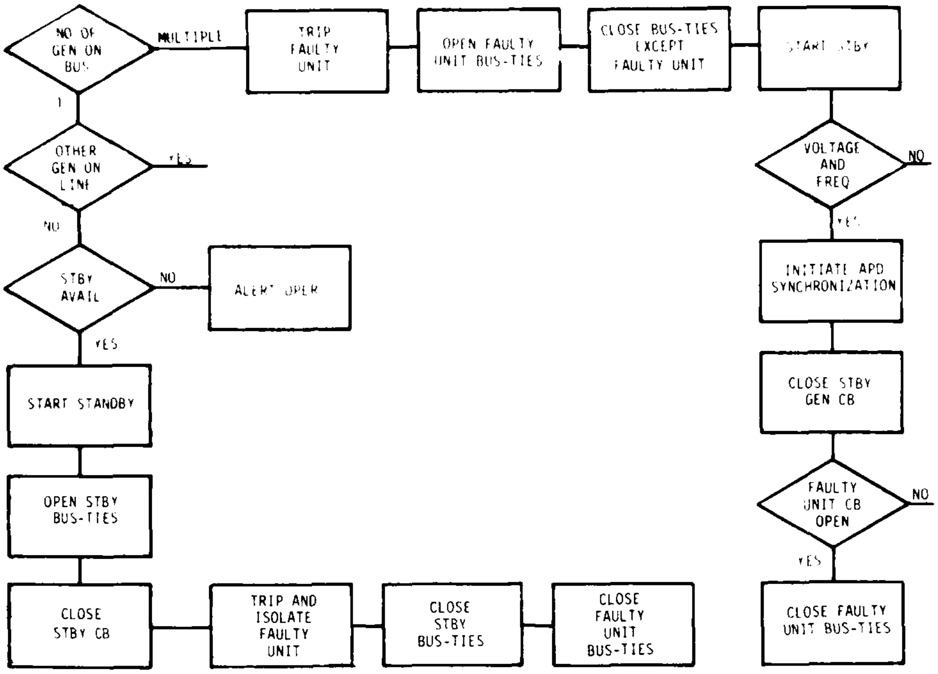



Figure 11. Logic for Correcting Bus Faults

the operator is alerted to the change by the plant corrected alarm, since there had been some kind of problem which should receive attention. The alarm light for the first detected fault will be flashing. If a fault still exists, indicating a problem with the governor or voltage regulator, the processor will shift to the routine where only one generator is on the defective bus. The logic for this routine is simplified to Figure 11.

Some additional comments about this supervisory system are in order. The faults that can result in corrective action will result in a flashing alarm and appropriate audible as soon as they are detected, telling the operator what the original cause was. Also some of the interim situations result in an overload of an operating generator. In that case the non-vital load shedding will occur and an alarm will alert the operator that this has happened. He can reclose the load shed breaker when he has sufficient capacity back on line. It is obvious that the supervisory system cannot correct the plant if there is no standby generator available. Fortunately, the normal load of the ship can be carried by two SSDG's, so there should be standbys on hand most of the time.

If for any reason it is not desired to use the supervisory system it can be placed in either the off or override mode. When in the latter mode all the alarms will be calculated and sounded but no corrective action will be transmitted. Power to the output relays is disconnected in both the off and override positions so no inadvertent commands will be given.

Use of the supervisory system will relieve the watch operator from his most critical decisions since he no longer will be faced with the need for instantaneous decisions for reconfiguration of the four engine plant. He will, of course, need to monitor the changes in load to determine what the proper configuration should be. If at any time he decides another SSDG is needed, he can start it up, bring it to synchronous speed and voltage, and then either synchronize automatically with the APD or manually with the synchroscope or lights.

## AUXILIARY CONTROL SYSTEM

The Auxiliary Control Console, Figure 12, is located in the Central Control Station at the bottom of a "U" formed by it, the Electric Plant Control Console, and the Propulsion Control Console. It provides monitoring, alarms, status display and controls of the following auxiliary systems:

1. Potable Water - tank level, high and low alarms, line pressure, fill valve control.

2. Distilling Plant - salinity concentration and alarm, sterilizer outlet temperature and alarm, dump value control.

3. Compressed Air - low and high pressure system emergency stop, pressure and temperature measurements and alarms.

4. Air Conditioning and Ships Stores Refrigeration - chill and freeze room temperature, alarm compressor status, and emergency stop control.

5. Starting Air -clutch control and status, lube oil pressure and alarm.

6. Bleed, Prairie and Masker Air - supply valve control and cooler discharge temperature and alarm.

7. Salt water service - overboard valve control, pressure reading and alarm, fire main loop pressures and alarm.

8. Chilled Water Circulation - temperature, pressure and expansion tank level, with alarms on all three.

9. Waste Heat Water Circulation - circulate pump run/stop control, pump discharge temperature, heat exchanger outlet temperature, and alarm compression tank level and alarm.

10. Drainage - bilge level alarms, oil waste holding tank level and alarm.

11. Sewage Disposal - holding tank and ejection tank level and alarms, macerator, comminutor, pump, and compressor running status.

12. Machinery Space Ventilation - vent fan start/stop control.

13. Fuel Filling Transfer and Purification - purifier, stripping and transfer pump, emergency stop, purifier pressure and vibration alarms.

14. Damage Control Monitor - emergency condition summary alarm from damage control console.

### Panel Layout

The organization of the console is arranged to provide rapid location relationships of the machinery elements within the ship, to assist the operator in his decisions for proper action. His displays and controls are those needed to monitor the systems and to take corrective action in case of out-of-tolerance operation. In only a few cases does he have a routine duty to perform.

Locations of sensors or controlled devices are arranged by bulkheads for each subsystem, with the locations further identified by the machinery space.

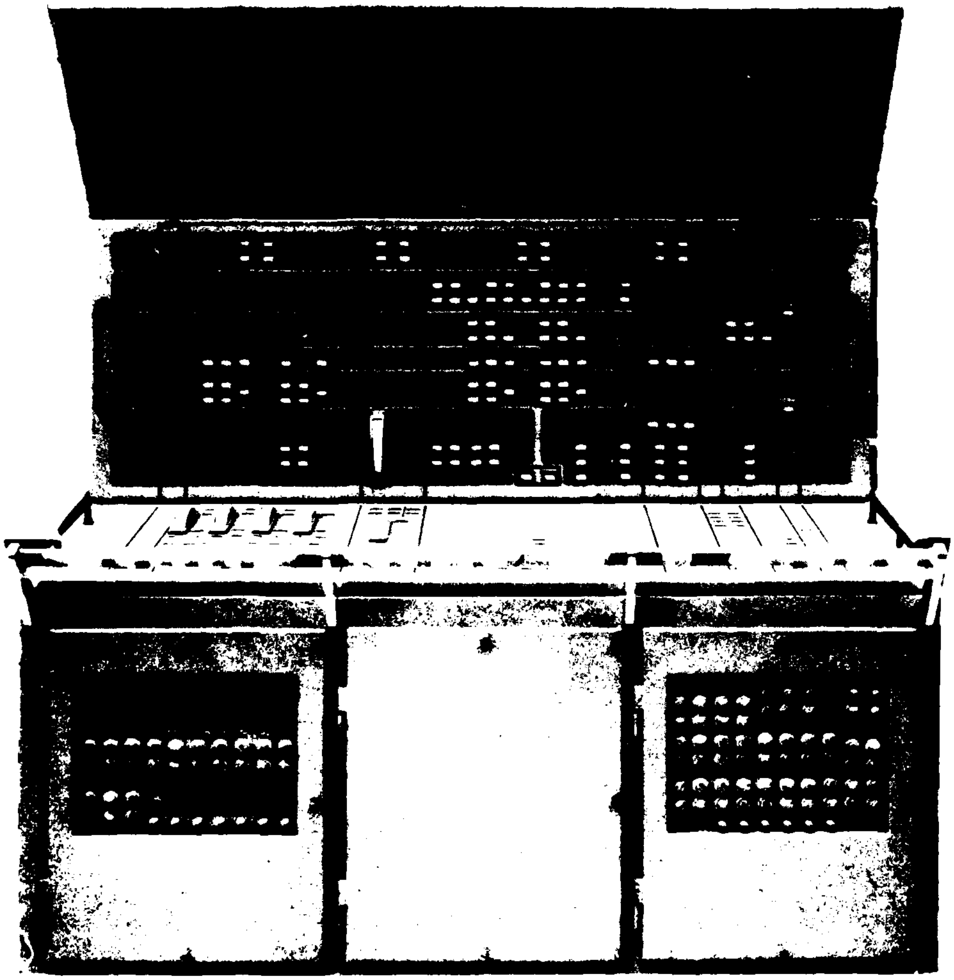


Figure 12. Auxiliary Control Console

### Data Handling

The sensor and discrete alarm data peculiar to the auxiliary systems comes directly into the console, where it is signal-conditioned and scaled.

There is an alarm system in the console, and all analog alarms are generated within the console-mounted electronics. As is the usual case, an alarm indicator will contain the address for dialing up the demand display for value readout. In this console there is an analog multiplexer, analog-to-digital converter, digital multiplexer, and line driver/receiver arrangement which transmits the data to the processor in the Electric Plant Control Console. There it is formatted and held in random access memory, to be fed back to the light emitting diode display on the Auxiliary Control Console, when addressed.

Because of this cross connection and a simiiar connection between the EPCC and the PCC, it is possible to display any available parameter from any console on any of the nine demand displays. This is a distinct advantage when the operator wants to observe a parameter from one console over a period of time without tying up that console's displays.

## DAMAGE CONTROL CONSOLE

The Damage Control Console (DCC), shown in Figure 13, is located in the central control station, forward of the of the Propulsion Control Console, in the area designated as the damage control central. The DCC provides status and alarms for the various sensors located through the ship, and also provides control of the valves and pumps in the fire main system.

### Displays

The upper panel of the console provides a spatial display of the many damage sensors for fire, smoke, and flooding, with alarm indicators placed to indicate the approximate bulkhead location of the sensor. The sensors are also grouped horizontally in functions. Another display provides status of the fire fighting systems; i.e., Halon and Aqueaus Film Forming Foam (AFFF). If the system has been activated by its local control, that fact is displayed at the console. The same type of display is provided for the sprinkling system. Display of the running or off status of the ventilation system is also provided. Ducting closure open/close, recirculation fan running/stopped, supply fan running/stopped and exhaust fan running/stopped indicators provide status of the system to the operator.

A control is provided to close all fire doors in the ship if the operator decides such action is required. These fire doors are normally actuated by local controls, but they may be remotely closed from the Damage Control Console.

The lower panel of the DCC is shown in Figure 14. The piping for the fire main is red on the actual panel, providing a vivid picture of the piping runs and the valve and pump location. Again the layout shows the near bulkhead reference point for the devices.

A continuous display meter shows fire main pressure in each of the upper and lower loops. (There is no demand display on this console). Each of the five fire main pumps may be started or stopped from the panel, suction and discharge valve status is indicated on the panel.

There are 20 loop valves that may be opened or closed from the panel to set up the required pumping arrangement. In addition, there are 79 manually positioned mimic indicators that are operator aligned to indicate the status of the corresponding manually operated valves in the fire main system.

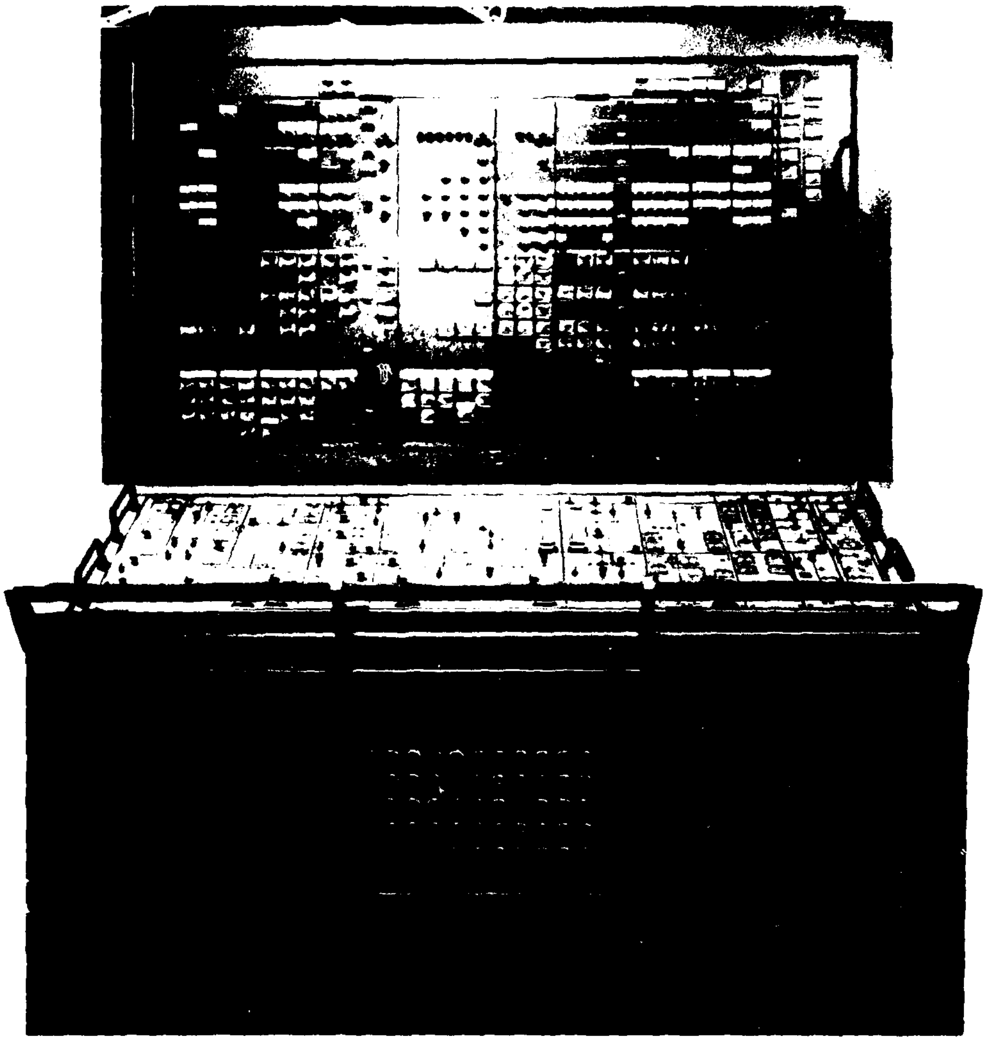


Figure 13. Damage Control Console

A new engine, even with its aircraft background and theoretically evaluated performance, leaves the controls designer with many ill defined characteristics. If he intends to use his system to operate more than one engine type, even if the other engine has known characteristics, he needs additional degrees of adjustment freedom.

There is,therefore, a requirement to have a great deal of flexibility to change system characteristics as well as numerical datums particularly on development units. This range of adjustments using variable potentiometers is a major source of unreliability in any system hence, as characteristics become established, the number of such potentiometers must be reduced. Where some flexibility to cater for engine types needs to be retained, they can be replaced by accessible replaceable fixed value resistors.

Table 1 shows representative samples of the anticipated progression in the reduction of adjustments for one part of the system, from initial development units to the prototypes of production units required to operate the SM1A endurance test module.

The adjustments specified for the production units can be categorised at four distinct levels:-

(a) Those required during the manufacture of the individual circuit cards to ensure that the effects of tolerances of individual components are removed. These would not be accessible or available for adjustment once the card had been tested and would generally be achieved by the individual selection of fixed resistors.

(b) Those required to prepare the system to suit a particular engine type or application. These would be defined changes using predetermined fixed value resistors and would be accessible after unit completion for the supplier or engine manufacturer to carry out the changes. These changes would be identified by a unique unit type number.

(c) Setting to work adjustments which must be readily available to optimise the control performance to a particular engine, its control system components and other interfacing machinery, in the new installation. These will also be required to retune the system when a major component is replaced.

(d) Operator adjustments, which must be available during normal operation to correct for deterioration in plant performance and changes in environmental conditions. The number, degree and scope of these adjustments should be very small.

The adjustments qualified in (c) and (d) require to be variable potentiometers with direct access from the front panel of the electronic unit. They are not identified as different categories except by the emphasis placed on them in the operating manuals. The intention is to continually assess all adjustments during the unit development and reduce their number wherever possible. Those that remain are required to be independant of each other and to have defined characteristics. Setting up is required to be achieved against a test simulation, without running the plant, to a level which will allow safe efficient operation without further adjustment. If on-line trimming is then required to optimise performance, concise calibration data and setting instructions will be provided in the operating manuals.

Maintenance and Diagnosis

The philosophy adopted in the display of information is to provide only sufficient data to the operations staff to indicate that the system is available and operating normally or that a fault condition exists or a trip has occurred.

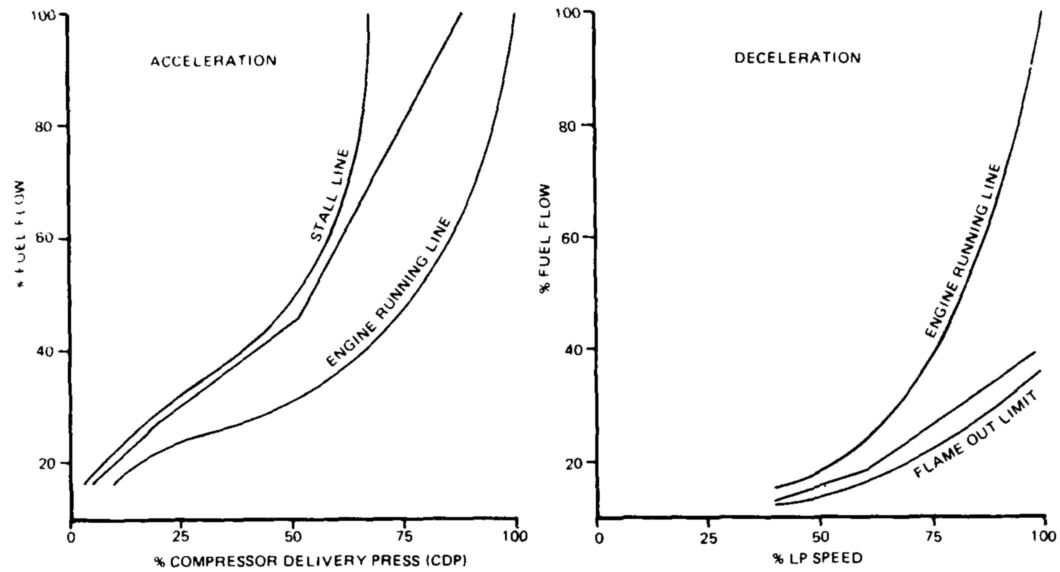



**FIG 4. ACCELERATION AND DECELERATION SCHEDULES**

transducers to be pre-selected from the standard range with special limits set on the direction and limit of drift due to changes in ambient temperature.

The original thoughts on deceleration control favoured the conventional jump and time rate schedule blending to a CDP limiting fuel schedule. In recent years, with the demands for efficient combustion, over the whole power range to reduce visible exhaust emissions, weak extinction limits have arisen whilst the desire of the operator to reduce power as quickly as possible, particularly during a crash stop manoeuvre, has not changed. Deceleration control has therefore become critical and is often required to shadow the running line as minimum fuel flow is reached. CDP transducers, as described earlier, do not achieve the high accuracy at near zero output required for deceleration control hence an alternative parameter was needed. LP speed is approximately 30% of maximum at idling conditions, its gain with fuel flow is high and it is slow to respond to partial flameout thus giving the engine maximum opportunity to relight before fuel is reduced. These, coupled with the high transducer resolution, allows fuel to be scheduled against LP speed, with accuracy and flexibility and without the need for additional transducers, a typical schedule is shown in Figure 4b.

Flexibility of Adjustments

A serious criticism of the hydraulic control was that datums could not be set up independently of one another without the need to ultimately run the engine at maximum conditions to set up full power. This was an undesirable situation if the ship was unable to put to sea or was operating in confined waters. The SM1A is required to have automatic two datum selection of all limiting parameters to achieve a higher power rating for emergency operation, hence the need for independance and off-line setting to work becomes substantially more important.

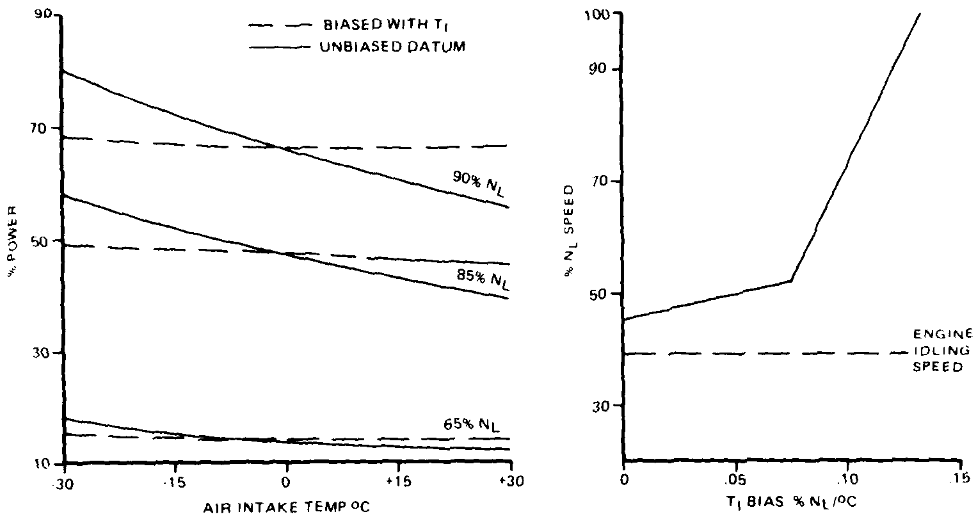



**FIG 3. INTAKE TEMPERATURE ($T_I$) BIAS OF LP COMPRESSOR SPEED ($N_L$) CONTROL**

Closed loop control using an engine output term results in a demand for additional fuel, up to the limit dictated by the acceleration control, if the value of that output falls. If an engine stall or flameout occurs due to some malfunction or failure condition, it is essential that the condition is recognised and fuel demand is decreased. Many ingenious methods have been employed to detect the onset of stall with varying degrees of success, however, these usually involve complex measuring and conditioning circuits.

Traditionally CDP has been used in air fuel ratio controls and similar devices to control acceleration and is still considered to be the best approach. If a stall occurs during acceleration CDP falls immediately, gas temperature rises quickly and the speed ceases to rise, an increase in fuel to achieve the desired speed would increase temperature further and rapidly cause an engine burn-out. Limiting the increase in fuel flow as a function of CDP, as shown in Figure 4a, would at the onset of stall, cause the CDP and hence fuel flow to reduce thus averting serious engine damage. If flameout occurs at any time the speed and CDP will fall, the speed control will demand extra fuel to achieve the desired level and the air/fuel ratio may increase to a level of 30:1 which is sufficient to cause a fire or explosion risk in the hot exhaust trunking. Again CDP scheduled fuel flow can be used to reduce this risk to a minimum, and in fact the same schedule as used for acceleration control is found to maintain the ratio above 60:1 which is well clear of the danger for spontaneous ignition.

If CDP is to be considered the aim must be to use a transducer with proven reliability and still attain the desired accuracy. Here the problem is less acute than for power control as the critical operating regime can be limited to the lower third of the pressure range, allowing the transducer to be optimised over a narrower band. After a careful study of the range of engine types, it was concluded that an accuracy of ± 5% of the desired fuel flow was acceptable. This still required

A major consideration in the new control was to choose a closed loop feedback of a gas generator parameter to provide high resolution of engine output with operator demand. In Reference 2 the choice of a parameter to fulful this need was studied in some detail and whilst no parameter had overwhelming advantages, compressor delivery pressure (CDP) was considered to be the best compromise. In considering this for the SM1A however, CDP was rejected on a number of counts;-

(a) Pressure transducers with established reliability and rugged construction were not sufficiently accurate over the large pressure range required to provide the desired resolution. The need to achieve accuracy of better than 1% of the selected level, particularly at lower power conditions, plus the effects of datum and temperature drift created considerable difficulties.

(b) There is a need for a compressor bleed at low power to assist engine handling on a high performance engine such as the RB244. The opening and closing of this valve caused significant changes in the CDP pressure versus fuel flow characteristic and control instability was a possibility unless hysteresis was built into the bleed valve operating system.

(c) It has been found that the use of CDP for control purposes does not eliminate the need for fuel flow measurement. Stringent requirements for acceleration control necessitates the measurement of both CDP and fuel flow and therefore the anticipated saving with a full CDP system is not borne out in practice.

(d) The operator's understanding of CDP as a control parameter to indicate the engine power state was poor.

In this last case, education is obviously a practical solution or the output can be displayed in terms of an accepted parameter such as rotor speed. However, having rejected CDP for range power control and because fuel flow has already been accepted as the fast control loop, engine compressor speed as the operators control parameter becomes a logical choice.

The output of speed using inductance probes measuring the passing frequency of a gear directly coupled to the engine rotor is both accurate, reliable and tolerant of large variations in power supply voltage. The measurement of gas generator low pressure compressor rotor speed (LP speed) is also necessary for limiting power and hence economies in circuitry can be achieved.

Its main limitations are that LP speed is non-linear with engine power and large changes in power occur with changes in ambient temperature at constant demanded speed. The first of these is conveniently resolved by shaping the speed demand characteristic to give the required selectivity over the full range of travel. In the second case, however, the customer required power changes, over the ambient temperature range -30 to +40$^{\circ}$C, to be controlled within $\pm$ 3% of the selected value which could not be achieved with simple LP speed control. This was resolved by biasing the rotor speed datum with a function of air intake temperature. The bias is arranged to provide negligible variation of power with temperature over the normal operating range but reduces to zero bias at idling speed. The effect of this bias is demonstrated in Figure 3. The additional benefits of this arrangement are that constant idling speed conditions are maintained, a characteristic which the operator uses as a reliability yardstick and the biased speed can be used to give the constant power limit, familiar in performance ratings curves at low ambient temperatures.

Having selected LP speed with an intake temperature bias as the range power control parameter, the important functions of acceleration and deceleration control need to be considered.

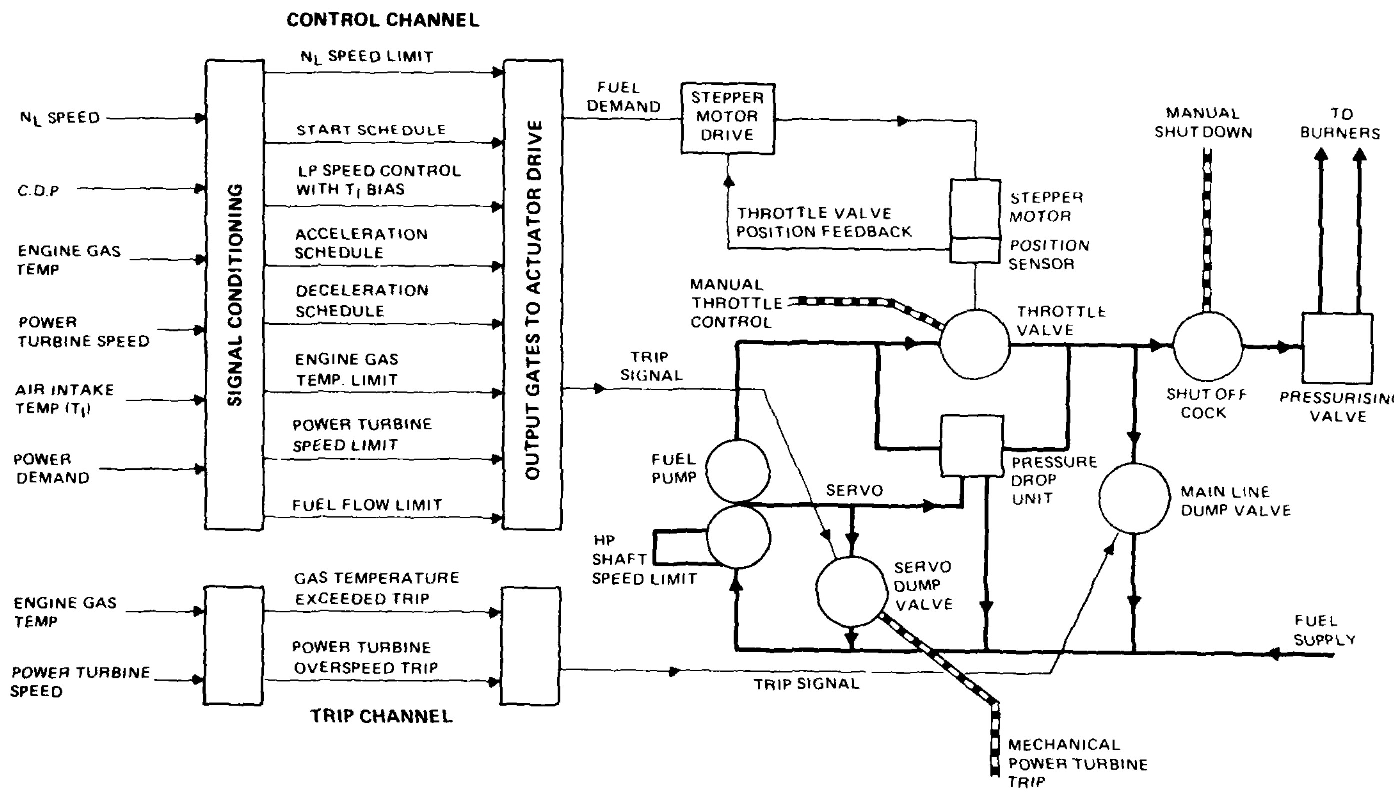



FIG 2. SM1A ENGINE FUEL CONTROL SYSTEM

In a comparative study it was concluded that both systems could be designed to demonstrate equal integrity but in the second case the electronic complexity to achieve this integrity was high with a consequential reduction in reliability. However, the fundamental objection to this approach was that the system could not be made to 'fail set' and allow take over in a manual mode if failure occurred in the electrohydraulic valve or the fuel flow loop.

The attractions of using the maximum electronics approach had been the reduction in complex hydraulic components which would be expected to reduce the influence of fuel contaminants. This, however, needed to be balanced against the potential of a hydraulic device, with millions of flying hours experience using flow control techniques, coupled with the availability of materials expertise gained in the marine environment with existing hydromechanical systems.

### The Basic System

The foregoing paragraphs show the basic progression in the decision to accept analogue electronics for the control of the gas turbine engine and the degree to which conventional hydromechanical devices are retained because of necessity, experience or proven reliability. The system finally chosen is conservative in its move towards electronic techniques, taking the approach that all the gas turbine signals, their amplification and integration into control output functions can be combined into a single efficient electronic unit leaving the fast fuel control loop to be performed by conventional hydraulic means. Two exceptions, retained largely for integrity reasons, are the high pressure compressor shaft governor which is an integral part of the fuel pump and a mechanical overspeed trip directly driven from the power turbine shaft and mechanically coupled to the shut down devices. The system proposed is outlined in Figure 2.

## DESIGN PHILOSOPHY

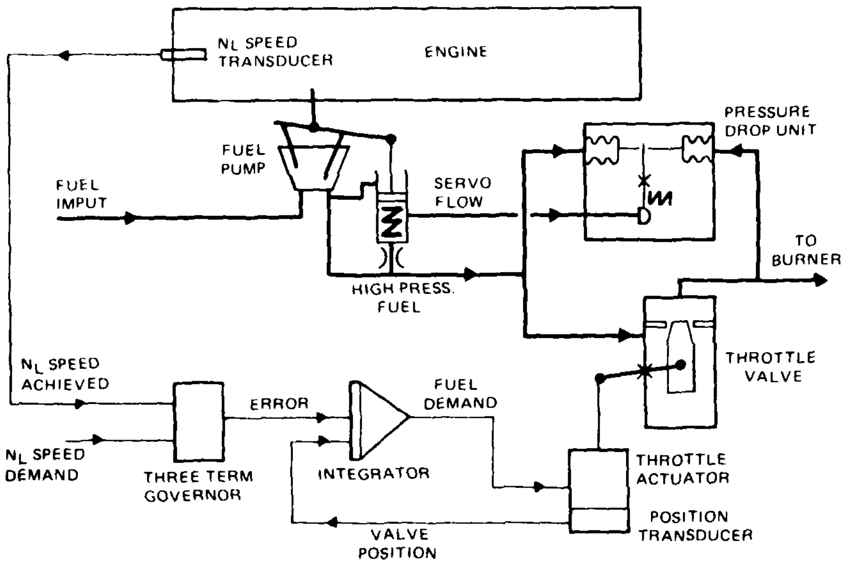
### General

Once the technical approach and the structure of the system has been established, the way is clear to specify the technical requirements. The aim must clearly be to learn from the experience of previous marine systems whilst exploiting the advantages and avoiding the pitfalls likely to result from the choice of analogue electronics for control computation. It was considered essential to employ a specialist company, with a wide military experience of analogue techniques, to provide the electronics expertise whilst using our own considerable marine background to provide the full systems engineering.

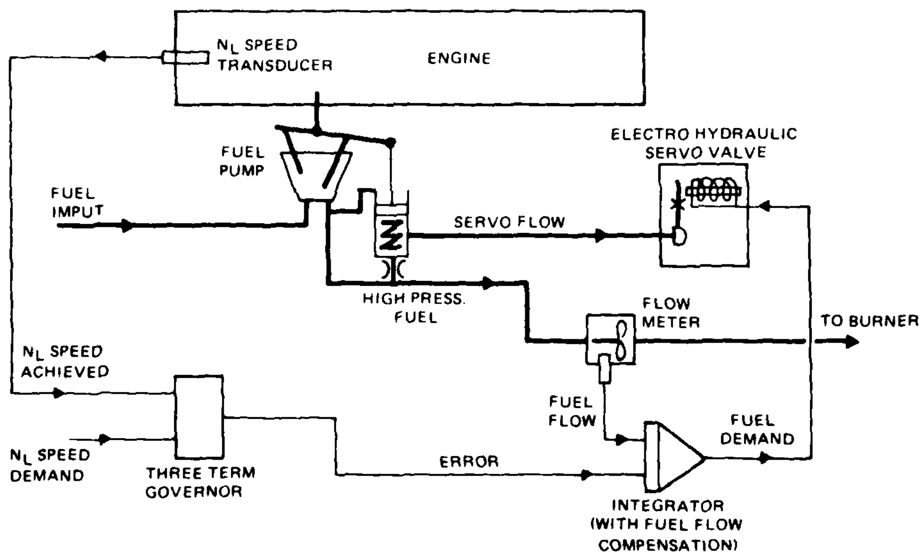
The problems of existing systems were well known and the advantages to be gained from the use of analogue electronics had been defined but many other problems needed to be solved in order to generate a working specification on which the equipment supplier could base his hardware. This paper is not intended to provide a system specification but rather discusses some of the more interesting questions which needed to be answered before a working system could be produced.

### Choice of Control Parameter

The requirement of a modern gas turbine control system is to regulate the fuel flow with the minimum of manual intevention. The operator is required only to initiate a start, to change the demanded power and to stop the engine in normal circumstances. In this he is assisted by automatic functions which require a knowledge of the gas turbine state. Limitations are placed on the maximum power of the engine to avoid unreasonable incursions into areas where engine life would be affected. Hence engine gas temperature, compressor rotor speed and power turbine speed are used directly to effect this control.




**(A) SYSTEM WITH HYDRAULIC FLOW CONTROL**




**(B) SYSTEM WITH ELECTRONIC FLOW CONTROL**

**FIG 1. COMPARISON OF HYDRAULIC AND ELECTRONIC FLOW CONTROL**

(b) A marine application requires only a limited amount of computation to provide effective fuel control. This is well within the capabilities of the analogue system, hence there is little incentive to use a system with surplus capacity if there is an increased technical risk.

(c) In view of the last statement, it did not appear that there would be any major reduction in component count with a digital system as the gain to be expected by replacing numerous integrated circuits by single computing and storage elements would be off-set by the additional equipment required for analogue to digital and digital to analogue conversion. Reliability would not be expected to improve on a simple count and little evidence was available to show that the equipment would achieve higher reliability in the new environs.

(d) The experience of programming digital systems for fast response closed loop control appeared to be limited. Programming for the complete system needs to have a readily understood language which can provide easy access for engineers to change programmes both numerically and functionally without recourse to a software expert. It was not clear that programming methods had developed to this extent.

(e) There was little evidence that development costs of hardware would be significantly different for either system whilst there was clear evidence that software costs would be substantial for the digital system.

(f) The development of the microprocessor was in its early stages and rapid advances were expected within the period of a new engine entering service. There was a high probability that these advances would create new hardware or software which was not directly interchangeable with that existing and now made obsolete.

(g) The performing of sequencing, health monitoring and fault enunciation within the capacity of an economically sized processor made the change appear attractive. However, the extra programming required to add these functions and still to safeguard the integrity of the engine control emphasised the concern already expressed in this area.

Since making the decision to develop an analogue system for the warship control, studies have been initiated, on the possibilities and extent of use of digital systems, for industrial gas turbine applications. These studies serve to emphasise that the above fears were justified at the time. In most instances, even when one takes into account control of more than one engine and the more complex computing required for range speed power turbine governing with fast response to power changes, the arguments in favour of a change to a full digital system are by no means convincing.

How far do we go?

Any fuel control system must retain hydraulic components in order to move and regulate the flow of fuel to the engine. There is always a need for a fuel pump, shut down devices, a flow divider and burners. These components can be similar for all sizes of engine and where highly developed, reliable components exist these must be retained with the minimum of change.

Two approaches were considered for the remainder of the system, one using a conventional flow control system whilst the other preferred the maximum of electronic functions. Figure 1 shows diagrammatically the two approaches, both shown using fuel flow as the fundamental fast loop control feedback.

A control system based on existing units with changes which showed real improvements in operation, maintenance and reliability appeared to be the optimum solution.

WHY CHANGE AND HOW FAR?

Retain Existing?

The hydraulic fuel control system used on the Olympus and Tyne engines has proven reliability and is confidently accepted and understood by Operational Staff despite a number of limitations. Some of these limitations, explored in detail in a previous paper (Reference 1), could certainly be overcome, by attention to detailed design and re-organisation of component location to improve accessibility, with little extra development effort or cost.

The desire to explore electronic controls had been stimulated by the rapid advances in both analogue and digital circuits which promised cheaper, more reliable and consistent hardware which would be more flexible in achieving desired characteristics, easier to modify and could be maintained more effectively. It was not, however, easy to quantify these advantages against the ability of the equipment to withstand the machinery room environment and the specialist requirements of the application. In addition final cost and reliability is dependant on the specialist having an understanding of the application and the ability to meet technical and quality assurance standards.

In the event the decision to change from a developed hydraulic to a new electronic system was based on a number of factors that evolved during the SM1A feasibility studies to swing the pendulum in its favour:-

(a) A cost saving exercise on the low pressure compressor and the design layout of the power turbine did not provide facilities to drive accessories from their respective shafts. This prevented the use of conventional hydraulic signal generators. Inductive probes monitoring an internal signal generator would need amplification and then conversion to a hydraulic signal to interface with the existing fuel control system. This additional electronics coupled with the existance of electrically based temperature sensing, throttle actuation and overspeed trips made the integration of these into a single system eminently sensible.

(b) The Royal Navy policy was moving toward an increase in the use of electronic equipment in the control of propulsion machinery and specialist expertise was expected to be available within their engineering discipline.

(c) Rolls-Royce were gaining practical experience with analogue equipment in industrial applications and were formulating design proposals for a marine system.

(d) The timing of the SM1A engine development programmes became more closely matched to that thought to be required to develop an electronic system.

Digital or Analogue?

Rolls-Royce were gaining experience with analogue systems and had started to tackle successfully the problems that these new systems had brought. With the development of the micro-processor to replace the mini-computer, considerable pressure was being applied from the specialist manufacturers to move directly to digital systems for the SM1A. This was resisted for a number of reasons:-

(a) The time alloted to the development of the new engine did not allow for the additional risks of problems using a technology relatively unknown in a machinery room environment.

# SPECIFICATION OF A CONTROL SYSTEM FOR A NEW MARINE GAS TURBINE

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ABSTRACT

The decision to develop the Spey gas turbine for marine propulsion provided the opportunity to introduce new control system technology. The experience gained with the Olympus and Tyne systems over a twelve year period identified the areas needing improvement and could be coupled with recent technological advances to produce a system for the 1980's. The design of the control system has progressed to the stage where breadboard systems are in development use.

The paper does not discuss the hardware employed but rather the interpretation of the customer's statement of requirements into a working specification. The subject matter concentrates on those aspects where there are a number of alternative approaches or where conflicts between requirements exist and analyses the route to the adopted solution. These aspects include the choice of system technology and its integration with proven components, the selection of parameters to provide optimum system control, the design to achieve rapid diagnosis, repair and setting to work without complex test equipment and the degree of redundancy to achieve high integrity whilst avoiding conflict with reliability requirements.

The hardware designed to meet these requirements will be rigourously tested to prove that the engineering approach is justified for the SM1A project. However, the paper, in drawing to a conclusion poses some of the questions which were answered in achieving a solution leaving the reader to judge if his approach would have been similar.

## INTRODUCTION

The Marine Spey RB244 engine is being developed from its successful aero counterpart by applying the expertise gained on other aero-derived marine engines and changing aerodynamic features not consistent with sea level operation. The gas generator is coupled with a new power turbine and integrated with its various systems to produce a propulsion package known as the SM1A module.

The fuel control system requires to be developed specifically for the SM1A and at the same time incorporate improvements which overcome limitations in existing systems. It is anticipated however, that the SM1A will be used for a wide range of naval warship applications both within the Royal Navy and elsewhere and may be required to operate with other gas turbines from the Rolls-Royce range. The control system, as specified, must therefore be suitable for the range of engines and applications with the minimum of change.

A programme was initiated to study the advantages of electronic equipment for fuel control in 1972, well in advance of the decision to develop the SM1A module. However, the controls programme had not reached a decisive point and the engine development programme appeared to be too intensive to allow for the development of a new control system. There was, in addition, the desire to build a minimum cost engine, hence to embark upon new control concepts did not appear to be justified.

Grounding and Shielding. Suppression of electrical noise on a system of this size, operating in a ship environment, and with high and low level signals transmitted over long distances requires rather rigid adherence to standard noise reduction policies. Originally planned to operate from a DC supply system but later changed to AC, the consoles nevertheless had to operate in isolated, above chassis mode. Obviously there had to be a common reference point for power and signal returns, and this was established at the backplane of each PWB, with all backplanes being wired together with many common wires. Interconnecting signals are transmitted over twisted pairs which helps to keep high frequency signal interaction to a minimum.

Shielded cabling, both inside the cabinet and for ship cabling, has been used throughout. The rule for grounding shields is that a low-level signal, on twisted shield pair, has its shield tied to the signal return at a point as near the receiving amplifier as possible and at no other point. Noise generating signals, either on shielded, twisted wire or on twisted wire in a cable with an outer sheath, have the shield connected to ships chassis at both ends.

With these grounding practices, the use of noise suppressors on contacts and solenoid coils, and judicious routing of cabinet and ship cabling, noise problems have been kept to a minimum. It was important that the ship builder required all interconnected equipments to conform to the same ground rules. It is somewhat difficult to maintain the isolation originally realized.

Demand Displays. The demand displays referred to throughout the above descriptions provide several benefits for the operators. Equipped with a four-digit, moving decimal LED display, with $\pm$ sign, and adjacent three-letter engineering unit designation, they provide more accurate readings than the meter displays. Thumbwheel switches permit rapid selection of a three-digit address which is listed on the console in two ways. Each analog alarm light has the address for its value engraved in the lens, and other data which has no alarm has the address silk-screened on the mimic in a functional area representing the sensor location. In addition, the addresses are listed numerically on panels adjacent to or above the mimic areas.

One very beneficial use of these demand displays is their use as a voltmeter in adjusting alarm level and other operational comparison levels. An analog signal is dialed up and its value read, then a switch near the display is operated to the alarm set position and the value for the corresponding alarm level is displayed. It can be read while the adjustment is being made. Operating a second switch on the demand panel permits the display of the alarm reset value, which is different from the alarm set-point by the amount of hysteresis desired. These switches permit the operator to assess his relation to alarm conditions without reference to listings or other documents.

## SUMMARY

The Oliver Hazard Perry class of Guided Missile Frigate is equipped with a modern, digital and analog control system using solid state electronics which provides automated controls for optimum performance and minimum operating personnel.

The use of small digital computers with read-only memory for automated propulsion control, electric plant supervision, demand data and data logging, and the use of solid state logic elements has permitted the accumulation of hundreds of data and logic decision functions into relatively small areas. Indeed, the space requirements are largely determined by the size of the related displays.

Close cooperation between suppliers and the ship builder provided a ship which went through its sea trials with exemplary results and one in which the crew, after weeks of shakedown cruises, has professed a high level of pride and confidence.

Each panel has lamp test circuits that can be used to determine if there is a live lamp in the indicator.

These circuits are diode isolated so they will only work together when being tested, and in some cases, where the lamp is turned on by a function which inputs data to the processor, they are further diode isolated to keep a false bit out of the processor during lamp test.

The meters used on the consoles are either switchboard-type from MIL-M-16034 or edgewise type, generally in accordance with MIL-M-24359. The one milliampere movements of the latter are driven from the electronic circuits through appropriate dropping resistors.

Logic Assemblies. The printed wiring boards, which are 8.5 by 4.5 inches, have a double row 78-pin connector which plugs into a mating socket by inserts into a plate. The back of the socket pin is extended to accept three layers of wirewrap connections and the entire matrix of 39-pin width and 31-PWB length constitute an assembly that is machine wire-wrapped at the factory. Keying of the PWB's is provided to eliminate damage to a board by plugging it into a wrong socket. The slides in the sides of the assembly keep the cards isolated from each other and a cover is placed over the end opposite from the connector to hold the cards in place during shock or vibration.

Card slot reference designations are marked above each slot and a reference list fastened to each rear door, identifying the type of card assigned to each slot. There are test points and adjustments on the rear of each card and an additional bank of wired in test points on the top of each logic assembly.

Power Supplies. One requirement of MIL-P-24423 is that any AC-to-DC converters in the consoles be provided in pairs, with each converter capable of handling the entire connected load. Therefore each console has rectifiers and regulators to provide +28 V DC for lamps and relays, +24 V DC for pressure transducer excitation, +5 V DC for logic circuits and ±15 V DC for signal conditioners and reference voltages. These voltages are regulated, too, one percent for data voltages, one percent for logic, and three percent for indicator and control. They are diode-coupled at their output and have current limit, overvoltage, and line variation controls which make them practically impervious to external irregularities.

Each console has a monitoring and display system for the power supplies that determines when any individual source has fallen below its reference value, and turns out the display light at the top of the panel.

Subassemblies. Other functional units in the consoles such as relays, diodes, transducers, and fuse panels are mounted on separate assemblies, either panel-available or on slides, and are connected to ships cabling or panel and logic assemblies by separate cables having keyed, locked-down connectors.

Alarms. All of the consoles have the same type of alarm system described for the Propulsion Control Console, except the DCC does not have a backup. Another feature of the alarm system is the first alarm capture, which causes the first alarm of any level to operate a blinking light and sound an audible, but to hold any subsequent alarm in that level to a steady light condition. This permits the operator to determine which of a related group of alarms was the first, as an aid in troubleshooting. As previously mentioned, acknowledging an alarm, by pushbutton, will change the blinking light to steady, and silence the audible. The light will stay illuminated until the fault condition goes away.

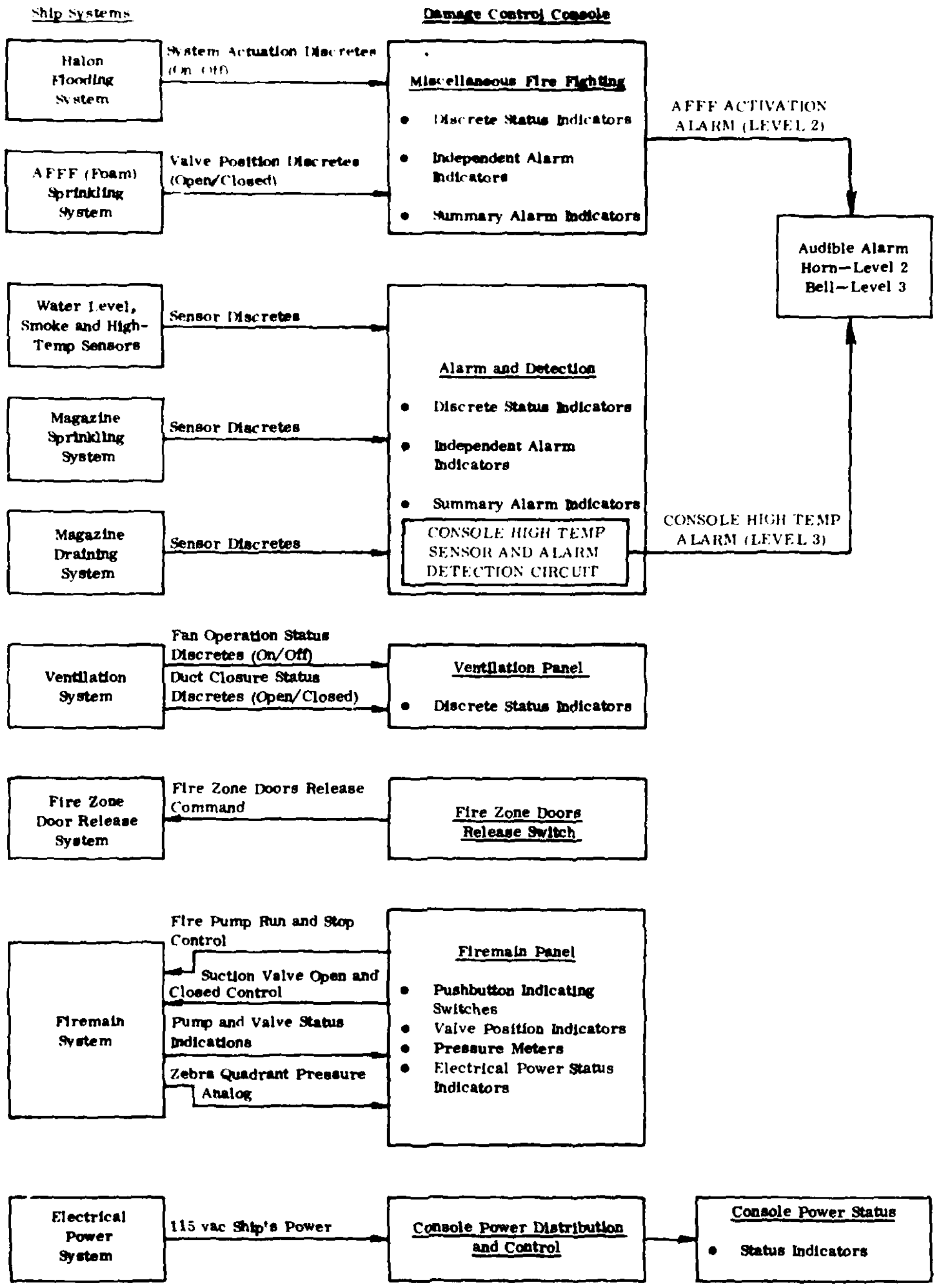


Figure 15. DCC and Ship Systems Functional Interfaces

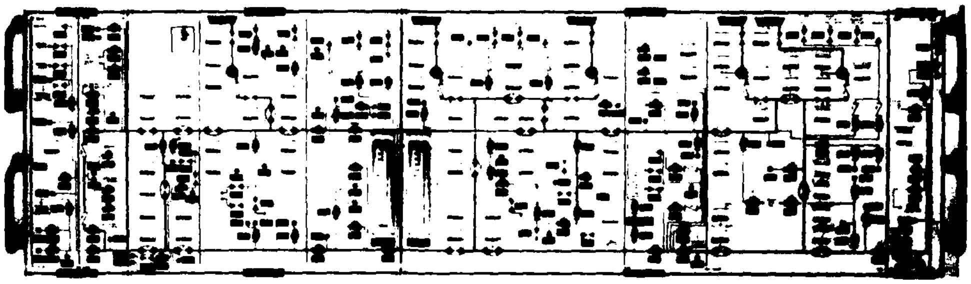

Figure 14. Fire Main Control/Display Panel

The three loop isolation values are outlined to indicate their significance in the valve operation to isolate the pumps and piping system for specified reasons. Various discharge paths for other users of the seawater supply are shown in other colors to remind the operator of potential loads. Manual valve indicators show whether or not the valve has been positioned to drain from the system. Lighted indicators show when one of the locally controlled valves for AFFF activation has been opened. A block diagram showing the functional interfaces with the ship systems is shown in Figure 15.

EQUIPMENT CHARACTERISTICS

Specifications

The machinery control equipment has been designed and qualified to the requirements of MIL-P-24423 (SHIPS), which imposes some rather stringent environmental requirements as well as defining standard part selection and drawing practices that closely regulate the suppliers activity.

Primary environmental requirements are:

| | | |
|---|---|---|
| 1. | Temperature | - $0^o$ to $50^oC$ operating |
| | | - $20^o$ to $65^oC$ non-operating |
| 2. | Humidity | - to 95% |
| 3. | Pitch | - 10 degrees |
| 4. | Roll | - $45^o$ from vertical |
| 5. | EMI | - MIL STD - 461 Class II |
| 6. | Vibration | - MIL STD - 167 type 1 |
| 7. | Shock | - MIL-S-901C Grade A, Class I Type A |

Hardware Design

Panels. The display and control panels are all removeable. In addition the vertical panels on the Local Operating Panel and Local Operating Station Indicator Panel are hinged to permit access to the rear of the panel, since in those assemblies there is no rear access to the console. The layout of panel components is based on a simplified mimic philosophy, which shows those elements of control or monitoring which will increase the operators ability to make decisions.

Indicator lamps and lighted pushbuttons switched are in accordance with MIL-S-22885 and are equipped with colored diffusers to provide the proper indicator. Multiple lamping is provided for these indicators, to provide indications for lamp burn out of these rather short-lived lamps.

TABLE 1. REDUCTION IN ADJUSTABLE PARAMETERS DURING TRANSITION FROM DEVELOPMENT TO PRODUCTION

| Adjustable Function | Dev. Unit Potentiometer Required | Prototype/Production Units | | | | |
|---|---|---|---|---|---|---|
| | | Requirement for Adjustment | | | Accessibility | |
| | | Change Engine Type or Application | Commission or setting to work | Drift Optimisation | Front Panel Potentiometer | Board Mounted |
| START SCHEDULE | | | | | | |
| Light off flow | ✓ | ✓ | | | | P |
| Rate of fuel incr. | ✓ | | | | | R |
| Light off detected | ✓ | | | | | R |
| Idling speed switch | ✓ | ✓ | ✓ | | ✓ | |
| Idling fuel flow | ✓ | | | | | R |
| $T_1$ BIAS OF $N_L$ SPEED | | | | | | |
| Scale Factor | ✓ | | | | | R |
| Multiplier Offset 1 | ✓ | | | | | P |
| 2 | ✓ | | | | | P |
| IDLING SPEED | ✓ | ✓ | ✓ | ✓ | ✓ | |
| ACCELERATION SCHEDULE | | | | | | |
| 1st. Slope | ✓ | ✓ | | | | P |
| 2nd. Slope | ✓ | ✓ | | | | P |
| 3rd. Slope | ✓ | | | | | |
| Origin | ✓ | ✓ | | | | P |
| 1st. Breakpoint | ✓ | ✓ | | | | P |
| 2nd. Breakpoint | ✓ | | | | | |
| ENGINE LIMITERS | | | | | | |
| Power Output { Normal | ✓ | ✓ | | | ✓ | |
| Power Output { Emergency | ✓ | ✓ | | | ✓ | |
| Power Turbine Speed { Normal | ✓ | ✓ | | | ✓ | |
| Power Turbine Speed { Emerg'cy | ✓ | ✓ | | | ✓ | |
| Gas Temperature { NC* | ✓ | ✓ | | | | R |
| Gas Temperature { NF* | ✓ | | ✓ | ✓ | ✓ | |
| Gas Temperature { EC* | ✓ | ✓ | | | | R |
| Gas Temperature { EF* | ✓ | | ✓ | ✓ | ✓ | |
| HP7 TRANSDUCER TRIM | ✓ | | ✓ | | ✓ | |
| STEPPER MOTOR DRIVE | | | | | | |
| Fuel Demand Scaling | ✓ | | ✓ | | ✓ | |
| Current Limit | ✓ | | ✓ | | ✓ | |

P = Potentiometer
R = Fixed Resistor

NC* = Normal range coarse control
NF* = Normal range fine control
EC* = Emergency range coarse control
EF* = Emergency range fine control

The front panel of the electronic unit is required to contain maintainer and diagnostic information but this is not visible to the observer at the local control station unless the control cubicle door is opened.

It is the maintainer who will normally have access to the electronic panel display. This display shown as an example in Figure 5 has indicators mounted on the front face of the individual circuit cards. These identify the individual function which is in control and indicate the major circuit faults associated with that card's function which its safety circuits have detected. In addition to operator adjustments, previously discussed, test points are provided which give access to all the major control parameters used in the electronic computations plus the main fuel system pressures.

The maintainer will have facilities to monitor the operational indicators and local panel instruments during the normal engine sequence to establish and monitor trends. When deterioration is suspected or a more accurate assessment is required, the test points can be used to monitor particular parameters using standard range instruments or transient data recorders. In the event of a fault being indicated at a remote control station the area of the fault can be readily identified from the circuit card fault lamps and the appropriate test points can then be monitored to isolate the particular board or control sub-assembly.

Facilities are not provided at the remote control stations to override major control faults which cause direct reversion to the manual mode or to reset trips in the event of an emergency shut down. Identification of the cause must be made at the electronic control panel and a concious and disciplined decision taken to accept, override or reset a fault or trip as appropriate.

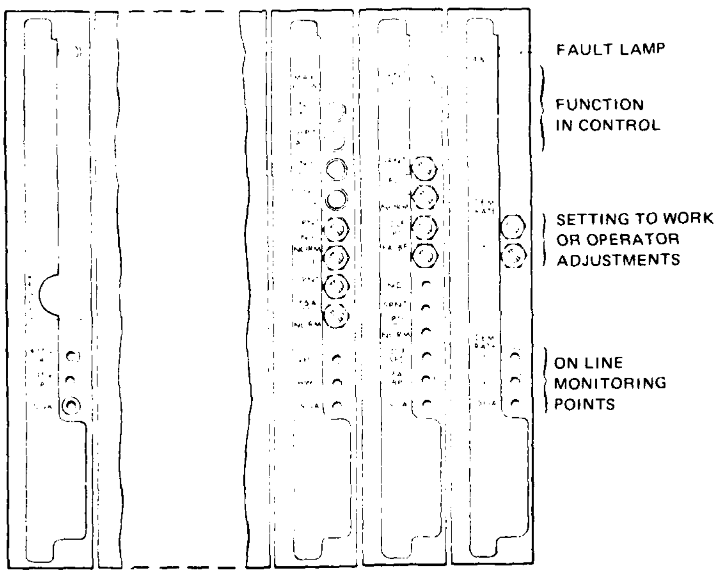


**FIG.5 ELECTRONIC UNIT FRONT PANEL LAYOUT**

The maintainer must, in addition to his facilities for diagnosis and monitoring of the control, be able to set up and test all the control datums.

Separate test equipment was specified initially to enable off-line checking of system functions, against a simple closed loop simulation and fixed reference datums, to be accomplished. Argument on the benefits of separate off-line, built-in off-line and built-in on-line test equipment have been considered throughout the early development.

We firmly believe that on-line testing is necessary to detect and indicate major circuit faults and to automatically revert to the manual mode if the fault results in an unacceptable operating condition. This, plus comparative checking of duplicated transducer circuits and verifying that other major functions are within reasonably safe limits, produces optimum safety without a serious reduction in reliability.

In a manned environment it seems reasonable to provide test equipment that can be used to check out the control at regular intervals during periods when the engine is not in use. Whether this equipment should be provided one to each engine or one per ship, stowed separately or built into the unit is debatable. The experience gained from testing the first units suggests that the functions can be located on a single circuit card and mounted in a spare location in the electronic unit. The main problem then is to house the front panel of this card, which is large because of the need to provide manual access to all the test functions. If this can be achieved it is highly likely that a built-in off-line test equipment will be accepted.

Reliability and Integrity

It is not intended to discuss the reliability and integrity of the SM1A module or the electronic control system as each could form a paper in its own right, the remarks here are limited to particular areas which have been given special attention.

It is a fundamental requirement of a naval warship that, as far as possible, any fault in the control system which, if undetected, would cause fuel flow to increase or decrease should be immediately detected and cause the control to 'fail set' at the last demanded condition. This allows the operator to take control manually at the gas turbine until the fault can be rectified or the engine is stopped. This manual control, on existing systems, is at the input to the hydraulic control and therefore pre-supposes that this fuel powered system has an inherent high integrity. A case of equal merit can also be established for the electronic system provided that power supplies can be guaranteed and a simple high integrity back up control lane is available to operate the throttle stepper motor. Power supplies can be guaranteed in three ways, by providing duplicated or triplicated sources of power from different ship supplies, by fitting a battery to the gas turbine module or by driving a power generator from the gas turbine. Whilst these alternatives each have their problems, they are by no means insurmountable. However, the scheme was firmly rejected in favour of achieving maximum operator confidence and highest integrity by direct manual operation of the fuel control valve. It is therefore left that failure of power supplies will cause the system to 'fail set' and allow reversion to the manual control at the SM1A module. At the same time however, it is recognised that the integrity of the power supplies, being used, is high.

The initial design of the manual drive was a hand wheel directly coupled to the stepper motor drive shaft. This was later abandoned in fa our of a direct coupling onto the throttle valve shaft because the stepper motor and the gear drive to the throttle valve were considered to be areas of potential failure and seizure due to their limited development experience.

The philosophy on Rolls-Royce marine turbines has been to provide a mechanical overspeed trip directly coupled to a fast acting fuel shut off device in addition to electrically operated trips, and in this the SM1A is no exception. On certain engines, such as the Tyne, where the power turbine is integral with the gas generator, this may not be practical. There is therefore, a need to provide dual channel electrical trips, to achieve the necessary systems integrity, in such applications.

The new control, in its role of applicability to a range of engines, was required to have a separate trip channel plus a trip associated with the control. The arrangement shown diagrammatically in Figure 6 shows a separate trip channel, detecting power turbine overspeed and excessive engine gas temperature, operating directly onto its own rapid fuel shut-off device and with facilities for separate and independent power supplies. In addition a trip datum is provided as a part of the power turbine speed channel, operating from the control channel power supplies and feeding directly into a second rapid fuel shut down device. This means that, if the trip channel is lost, the control will still be capable of performing its normal functions, with control limits set on all datums and the power turbine trip available, in the event of engine malfunction. If a major control failure occurs or its power supplies are lost the control will fail set. The operator can then control manually from the emergency station with the confident knowledge that he still has the backing of the independent engine trip channel.

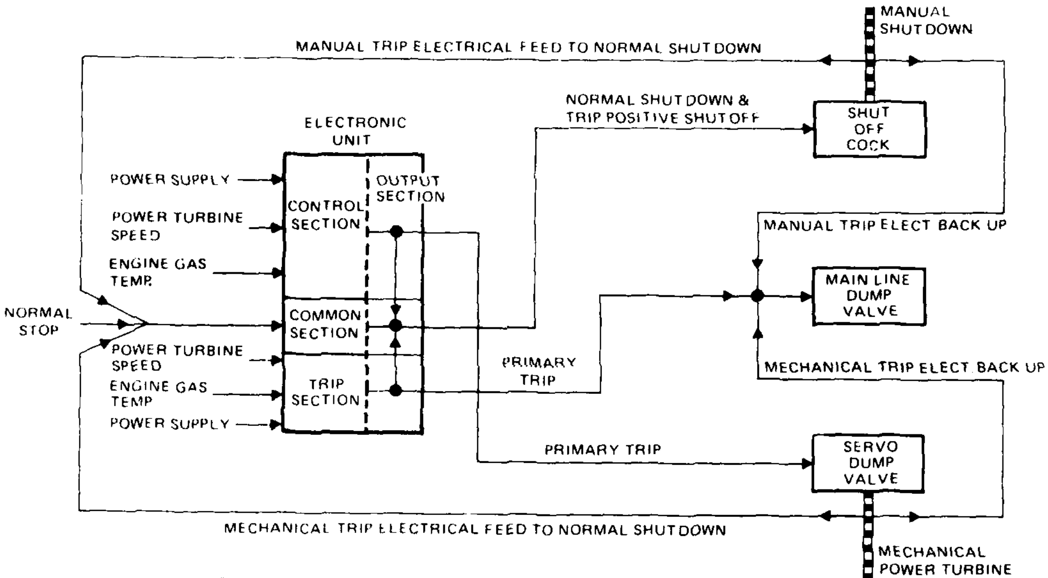


FIG 6. INTEGRATED GAS TURBINE SHUTDOWN SYSTEM

All the main engine control parameters are duplicated and the two signals are compared in the engine control electronics. Faults in either signal are required to be detected and an indication is given of a system fault if the comparison shows that one signal is out of limits, the control however continues to operate normally using the channel with the higher output. The engine temperature control and monitoring comprises a ring of ten triple element thermocouples measuring gas generator exhaust gas temperature.

Two sets of these couples are averaged one set being sent to the control channel and the second set is sent to the trip channel. This is necessary to obtain the specified accuracy of 1% on control and 2% on trip and to maintain the desired independance of the two channels. Carefully designed circuitry is required to avoid losing this independance and still be able to compare the two signals so that a fault is identified. The third set of elements is provided as individual outputs to the operator to allow him to identify temperature variation around the engine, for trend and health monitoring, as well as to average them for performance and surveillance instrumentation.

SATISFYING THE SPECIFICATION

In the early stages of the preparation of a specification, for a complex item of control equipment, for a new gas turbine and a future generation of warships, it is not possible to issue a comprehensive contract document. At the commencement of the project the electronic equipment supplier had an intimate knowledge of his electronics and was conversant with gas turbines, the engine manufacturer had an intimate knowledge of gas turbines but was unable to precisely define some parameters for the SM1A module. The customer knew ships and their controls intimately but had no clearly defined ship. The first document issued therefore, was a statement of requirements with many grey areas and some total blanks.

This was 'worked up' as design information and results from specialist studies became available, but considerable discussion took place between the three parties involved, to produce a working specification.

At the stage of preparing this paper, development units are available and are undergoing tests to prove that the statement of requirements and its intepretation into a functional system has been effectively carried out. The supplier has used theoretical engine simulation models to optimise the control characteristics of the equipment and has carried out functional and environmental test programmes. The equipment is now being used by the engine manufacturer to assess that it meets the spirit and intention of his requirement before being committed to run an engine.

The opportunity will be taken to test the control on an Olympus TM3B module before fitting it to the Spey RB244 gas generator. The TM3 engine has fully established control characteristics hence system optimisation can be carried out prior to the engine test. This test will be free from the pressures of a mechanical engine proving programme which gives the controls engineer scope to subject the system to a complete test series designed to prove its capabilities. This engine has also been used to test a number of experimental control systems, hence a direct objective performance comparison can be made with these systems.

Satisfactory completion of these trials will allow an early feedback of data into the design of the prototype equipment which is specified to full naval warship standards and will be used to run the full module endurance trials.

The initial programme is also designed to allow sufficient development of the gas turbine to take place on a well tried and proven system before integrating it with its new control system. The TM3 test programme is designed to establish the control system as a viable unit, in order to give the gas turbine engineer confidence that his development programme will not be jeopardised by unreliable equipment. Even when the engine and its control finally come together, much test running will be dedicated to specific performance and mechanical proving of the gas turbine and the controls engineer will have to fight hard to ensure that sufficient time is allotted, early in the programme, to matching engine and control characteristics. Once the system has been optimised it is essential that further adjustments are avoided so that consistent operation in all engine modes and environmental conditions can be established.

Simultaneously with engine testing, bench running will continue to attempt to anticipate problems during engine development, investigate difficulties that occur, assess reliability and integrity under adverse conditions and train personnel in the operation of the equipment.

## CONCLUSIONS

The decision to change from a reliable, existing control system with defined limitations, posed a series of questions.

Should we have changed to analogue electronics or taken the larger stride direct to digital microprocessor equipment?

Should the conservative policy, of retaining a basic flow control loop, have been adopted or should we have changed to a control with maximum electronics content?

Should we design a complex and expensive mechanical device to take over manual control in an emergency or should we have confidence in our electronic circuits?

Should we design a control to cover a wide range of engines and applications or use a dedicated approach?

Should we have specified full automatic test facilities capable of diagnosing detailed system faults or is a better balance obtained by retaining a large manual diagnostic content?

The answers to these and other questions discussed in this paper are not black and white but a complex balance of a number of factors. We believe that, in dealing with a military weapon, the overriding consideration must be the operational integrity of the ship and the safety of its crew. Inovation and new techniques can provide significant advantages, where existing equipment cannot cope with new operational demands, then change should be welcomed. We must not, however, thrust aside reliable, proven equipment for something with considerable hazards, which are unforseen because of its limited application in operational situations.

This philosophy has enabled us to solve the problems objectively and arrive at a clear solution for the SM1A project. The rigourous test programme to be undertaken during the gas turbine development will show that this engineering approach is justified.

## ACKNOWLEDGEMENTS

The Author acknowledges with thanks the assistance given by his colleagues in the preparation of this paper and the Industrial and Marine Division of Rolls-Royce Limited for permission to publish the work.

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# AN EVALUATION OF SIMPLIFIED PROPULSION CONTROLS FOR GAS TURBINE POWERED NAVAL SHIPS

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ABSTRACT

This paper describes the results of an investigation to determine whether a simplification of the propulsion control system can be achieved by a combination of the reduction of nonessential automatic functions and the reduction of displayed and monitored parameters.

The guidelines included: maintenance of the same level of manning; no loss in operational capability; maximum commonality of operator consoles at the Local Operating and Central Control Stations; and utilization of existing cards and circuitry to minimize new development.

The specific propulsion control and display functions associated with each of the control stations and their respective equipment consoles were analyzed, and the results quantified in terms of numbers of signals processed, operator controls, displays, and associated hardware.

From these results, conclusions were drawn concerning those areas that would provide the highest payoff and would most benefit by simplification.

Techniques for achieving control simplification examined were: deletion of automatic features for fuel oil, lube oil, bleed air, speed control, mode change, and start/stop gas turbine function. Similarly, monitoring simplification was examined in terms of reducing the number of sensors and analog displays, increased utilization of summary alarms, and minimization of logging functions.

Typical DD power plant controls were used as a reference baseline for this analysis.

It was concluded that reduction in automated functions, when combined with simplification of the monitoring and display parameters could result in a 50 percent savings in printed circuit cards alone.

The additional manual effort required by the operator, as a result of reduced automation, would serve to maintain his proficiency. The reduction in displayed parameters would serve to reduce his mental burden.

## OBJECTIVE

The objective of this investigation was to define a simplified, reliable control system with the following features:

- A minimum of automatic functions while maintaining the same level of manpower for ship control.

- A meeting of Human Factors standards for man-machine interfaces.
- A maximum amount of commonality between the Central Control Station (CCS) and Local Operating Station (LOS) consoles to ease operator interface adaption.
- Automatic features necessary to protect the plant and ease the burden of complex control operations.
- Simplified status and alarm displays providing feedback to the operator.

Then compare the simplified system with the baseline DD to determine how much simplification is practical.

APPROACH

Ship control system simplification may be approached from two directions:

- Simplification of the hardware
- Simplification of the man-machine interface and degree of mutual interaction

A simplification in one direction may be at the expense of the other, and care must be taken to achieve a proper balance.

The emphasis in this study was on simplification of the hardware through first, reduction in automation, and second, reduction in the number of displayed parameters and simplification of the alarms. The principal reductions in the automation considered were:

- Deletion of closed loop rpm control and adopting open loop power control
- Deletion of automatic gas turbine startup/shutdown and mode change
- Deletion of automatic fuel oil, lube oil, and bleed air functions

Although the emphasis was initially on hardware simplification through reduced automation (and increased operator activity), it became apparent that in the display and monitoring area, both hardware simplification and man-machine interface simplification could be achieved by:

- Reducing the number of parameters displayed
- Use of summary alarms
- Replacing analog signals with discreets

Thus, the proposed simplified system has simplified automatic features and a simplified data system.

More sophisticated approaches, such as the use of computer-driven Cathode Ray Tube (CRT) displays, were not pursued, because this would be incompatible with the objective of minimum system redesign.

## DISCUSSION

### Baseline DD Control System

The baseline DD system is illustrated by the equipment family tree of figure 1 and the pictorial diagram of figure 2.

The equipment stations are located in the Pilot House, CCS and each of the Main Machinery Rooms. The CCS is the major control area of the ship and is the most extensively equipped. It contains the Propulsion Auxiliary Machinery Control Equipment (PAMCE) which provides the control and display functions for the main propulsion plants and the ship auxiliary systems. The Propulsion and Auxiliary Control Console (PACC) is the prime operating station for this equipment.

The Propulsion and Auxiliary Machinery Information Systems Equipment (PAMISE) accepts and processes operational data and provides outputs for real time display and recording of this data.

The Ship Control Console in the Pilot House provides command, control and monitoring for steering and propulsion.

Commands originate from the bridge with the option of propulsion control of the ship being taken by CCS.

The Propulsion Local Operating Equipment (PLOE) with its Propulsion Local Control Console (PLCC) provides single shaft control and display capability, including the two main gas turbines and the auxiliary machinery within the associated engine room.

## PROPOSED SYSTEM

The proposed control system includes three major equipment locations:

- Bridge--Throttle levers to vary ship speed and a control unit to receive information on actual speed and shaft rpm
- Central Control--A console to provide control and status information for the plant
- Local Control--A panel to provide control and status information for the plant in the engine room

The plant is generally operated from CCS by direction from the Bridge.

### Description

A description of the functional operation of each console was used as a starting point for the study. The rudimentary requirements were spelled out. They follow the philosophy of minimum automation. The integrated pitch/throttle control was retained to provide ease of operator control in the difficult crash ahead and crash astern maneuvers.

Bridge Console. The bridge control will consist of a panel and a dual lever (one for each shaft) that varies the desired ship speed, (forward and reverse) through central control and local control. The bridge control will be transmitted independently for each shaft. The

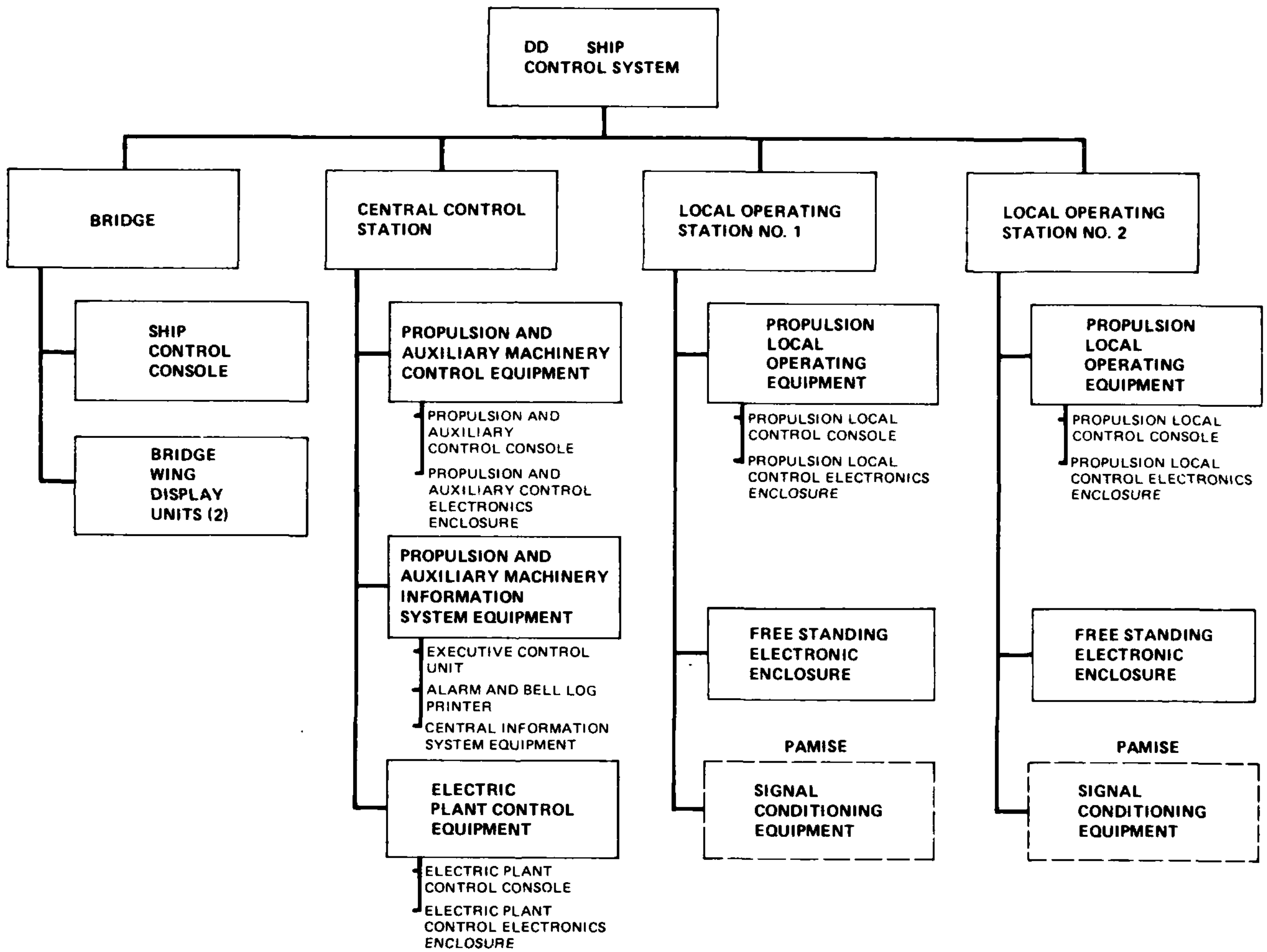


Figure 1. Equipment Family Tree.

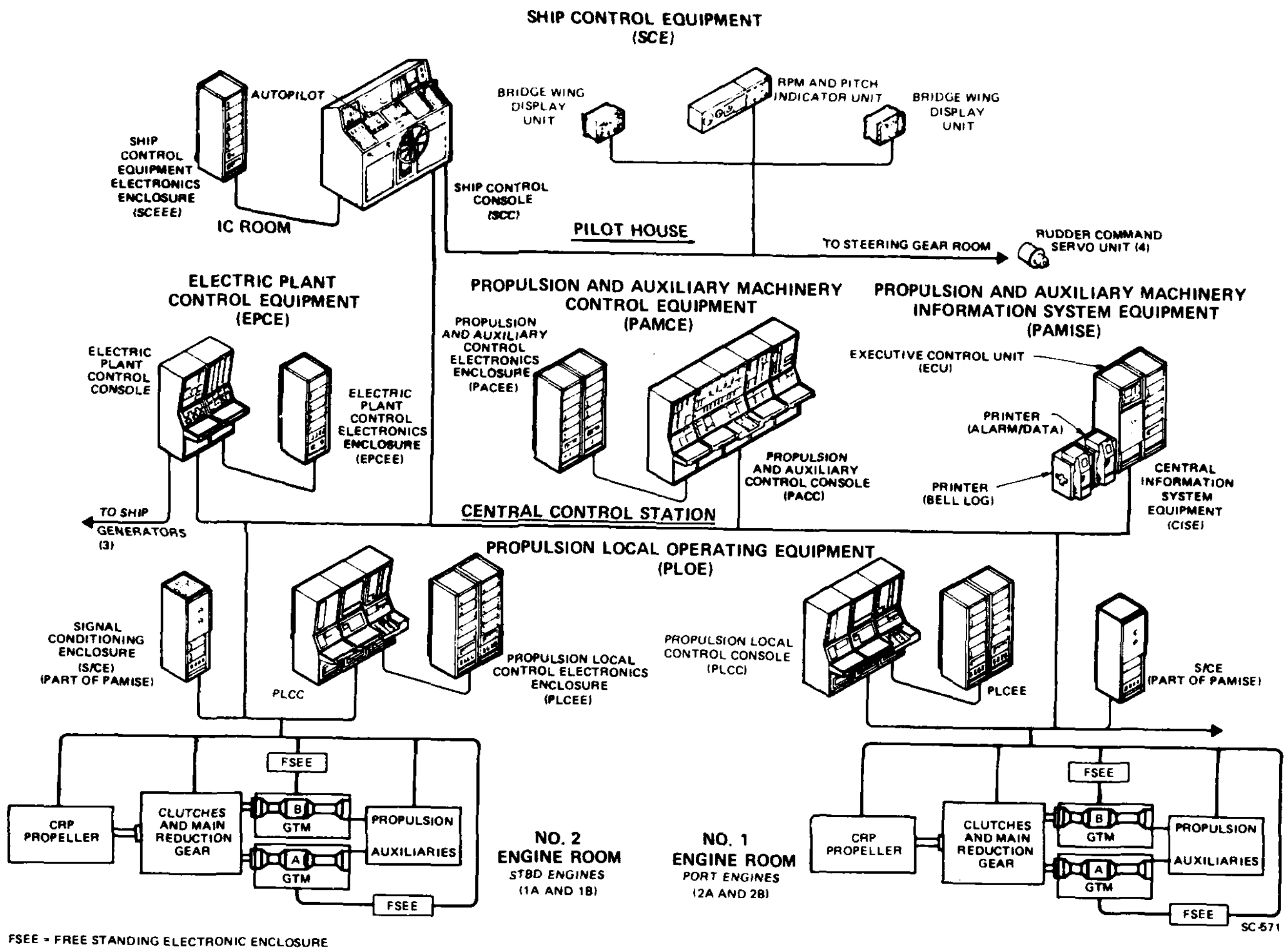


Figure 2. Baseline DD Propulsion Control System.

ship speed and shaft rpm, and propeller pitch will be displayed. The engines on line status will also be indicated. No bridge wing controls will be included, rpm and pitch meters for the bridge wings will be provided.

Central Control Console. The Central Control Console will be electrically linked to the engine room local operating panel and have all of the features of direct manual control. There is a minimum of feedback or automatic control at this console.

The Central Control Console will provide the following features:

- Integrated Throttle/Pitch Control--One lever/shaft. Also separate manual throttle control for each engine and pitch control for each shaft
- Shaft and power turbine rpm indication and torque indication
- Ship speed requirment from bridge and ship speed indication
- Engine status (for each engine)
- Auxiliaries status, instrumentation and alarms (LO & FO)
- Overtorque alarm (from torsionmeter and FSEE torque computer)
- Alarms and engine trip for engine low lube oil pressure and over temperature
- Startup and Shutdown manual sequence for each engine
- Brake engage/disengage manual control
- Clutch engage/disengage manual control
- Anti-ice--start/shutdown of system
- Alarms for shaft and gear bearing problems
- Turbine inlet temperature indication
- Blow-in door status
- Telephone communication with local control for control, if required
- Gas turbine module fire alarm status
- Bleed air initiation for PRAIRIE and MASKER
- Throttle transfer
- Fire fighting control ($CO_2$ inhibit)
- Controllable reversible pitch (CRP) status
- Engine overspeed trips
- Alarms for lube and fuel oil pressure and temperature

The torque limits in the gas turbine controls are retained to provide plant protection. Signal conditioning for signals coming from the engines will be provided. Data logging and demand display capability will be deleted from the data system.

In essence, the central control console will be manned continually and provide for manually carrying out:

- Readiness checks on status
- Startup/shutdown of engines
- Manual mode changes or change of engines within mode
- Acceleration of deceleration of shaft
- Propeller pitch change, including reversals
- Stop shaft/release shaft
- Monitoring of key engine and system parameters
- Throttle transfer from CCS to bridge and bridge to CCS
- Plant emergency control

Engine startup provisions and the mode changes to engage the engines are manual operations. Integrated throttle/pitch control is included so that crash ahead and reverse maneuvers can be facilitated. The power and propeller pitch are scheduled and controlled during these maneuvers.

Local Control Panel. The Local Control Panel will be electrically linked to the engine throttle actuator and have direct manual control. There will be no feedback or automatic control at this panel.

The local control panel will provide the following features:

- Throttle Control (one lever for each engine)
- Shaft and power turbine rpm indication and torque indication
- Ship speed requirement from the bridge, relayed from central control
- Engine status (for each engine)
- Pitch control (one lever)
- Auxiliaries line up status, controls, and alarms (LO & FO)
- Overtorque alarm (from torsionmeter and FSEE to torque computer)
- Alarms for low fuel pressure, low lube oil pressure
- Startup and shutdown sequence for manual control
- Brake engage/disengage control

- Clutch engage/disengage control
- Anti-ice start/shutdown of system
- Alarms for shafting and bearing problems
- Turbine inlet temperature indication
- Blow-in door status
- Communication with central control and confirmation of signal
- Gas turbine module fire alarm status
- Bleed air control for PRAIRIE, starting and MASKER
- Motoring control for compressor water wash and other purposes
- Elapsed time meter
- Throttle transfer
- Fire fighting control ($CO_2$ inhibit)
- CRP status and control
- Engine overspeed trips
- Trip and alarms for low lube oil pressure and over temperature

In essence, the local control console would be manned as required in an emergency to provide for manually carrying out:

- Line up of auxiliaries
- Startup/shutdown engines
- Mode change or change of engines within mode
- Acceleration or deceleration of propeller shaft
- Propeller pitch change including reversals
- Stop shaft/release shaft
- Monitoring of key engine and system parameters
- Throttle transfer from CCS to LOS and from LOS to CCS
- Plant emergency control

Requirements

There is no requirement for the accurate control of shaft rpm. There is no requirement for the time of mode change. There is no limit for startup or shutdown time. The only requirements are for:

- Operation over the total performance map (including one shaft operation)

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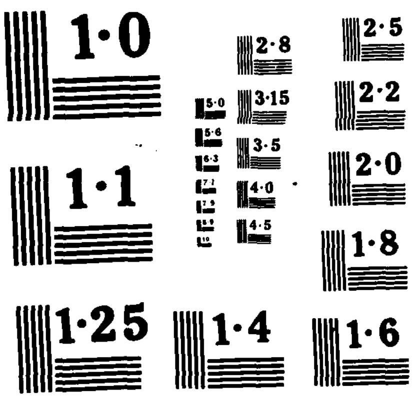
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- Active plant protection for all modes of operation

It is desirable that the control system power supplies be fed from a no-break battery power source.

The control consoles and panels will be shock qualified to Grade A shock as in the DD program.

The consoles and panels will meet human factors criteria for design. The CCS console should be operable from a seated position. The Local Operating Station Panel will be operable from a standing position.

REDUCTION OF AUTOMATIC CONTROL FEATURES

The following automatic features were proposed for deletion in the simplified system, as described in the previous section.

- Automatic fuel oil feature
- Automatic lube oil feature
- Automatic bleed air
- Automatic mode change
- Automatic GTM start/stop function

Auto Fuel Oil. The deletion of the auto fuel oil feature deletes the pump mode rotary selector switch from each PLOE and two pump mode rotary selector switches from PACC. It also eliminates three printed circuit (PC) cards from each PLOE.

Auto Lube Oil. The deletion of the auto lube function deletes the pump mode rotary switch from each PLOE and the two rotary switches from PACC. It also eliminates three PC cards from each PLOE.

Automatic Bleed Air. Elimination of the automatic features for the bleed air function plus a cleanup of eliminated bleed air functions deletes eight illuminated pushbuttons from each PLOE and also deletes three PC cards from each PLOE. This function deletion eliminates sixteen illuminated pushbuttons and four PC cards from PACC.

Automatic Mode Change. Deleting the automatic mode change function from the PACC deletes four pushbuttons, seven illuminated pushbuttons and ten indicators in addition to deleting forty PC cards.

Automatic Start/Stop Function. The deletion of the auto start/stop GTM functions deletes the two rotary mode selector switches, ten pushbutton switches and twenty-four indicators from each PLOE; it also deletes four rotary switches, twelve pushbutton switches and forty-eight indicators from PACC. In addition, it deletes eleven PC cards from each PLOE.

The above hardware items are the sum total of the hardware that can be eliminated by eliminating the automatic propulsion control features. The deleted items are totaled in table 1. Current interface requirements are unchanged from the DD.

Table 1. Savings: Deletions of Auto Functions.

| FUNCTION | PACC | | | PLCC (2) | | | TOTAL | | |
|---|---|---|---|---|---|---|---|---|---|
| | SWITCHES | PC CARDS | INDI-CATORS | SWITCHES | PC CARDS | INDI-CATORS | SWITCHES | PC CARDS | INDI-CATORS |
| DELETE AUTO FUEL OIL FEATURE | -2 | 0 | | -2 | -6 | | -4 | -6 | |
| DELETE AUTO LUBE FUNCTION | -2 | 0 | | -2 | -6 | | -4 | -6 | |
| DELETE AUTO START/STOP GTM FUNCTION | -4 -12 (PB) | 0 | -48 | -4 -20 (PB) | -22 | -48 | -8 -32 (PB) | -22 | -96 |
| BLEED AIR AUTO FUNC-TION DELETION | -16 (PB) | -4 | | -16 (PB) | -6 | | -32 (PB) | -10 | |
| DELETE AUTO MODE CHANGE FROM PACC | -11 (PB) | -40 | -10 | | | | -11 (PB) | -40 | -10 |
| | | -44 (15%) | -58 | | -40 (22%) | -48 | -16 ROT -75 (PB) | -84 (20%) | -106 |
| | -47 | | | -44 | | | -91 (TOTAL) | | |

The most significant contribution in terms of PC card savings was from deletion of the Auto Mode Change from PACC. The other changes produced only small simplifications.

Although there is a 20 percent savings in PC cards for the PACC and PLCC shipsets, this savings, by itself, is not considered sufficient. However, when combined with the monitoring techniques discussed in the following section, the total savings becomes appreciable.

Monitoring and Display Simplification.

In analyzing the display requirements, refer to the chart of table 2, which quantifies and summarizes the display signals which are processed by the various propulsion system control consoles.

It is noted that the major portion of these signals, 44 percent, are associated with the GTM, and that the PACC and PLCC consoles handle 90 percent of the total signals processed.

A major portion of the GTM signals are analog in nature. Thus the following methods of attack are suggested:

- Reduce the total number of signals displayed, with emphasis on those associated with the GTM
- Minimize the total number of analog signals displayed. Convert these to discreets wherever possible

Table 2. Display Signal Summary.

| DATA PROCESSING | PLCC NO 1 ANAL | PLCC NO 1 DISC | PLCC NO 2 ANAL | PLCC NO 2 DISC | PACC ANAL | PACC DISC | EPCC ANAL | EPCC DISC | SCC ANAL | SCC DISC | TOTAL ANAL | TOTAL DISC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EOT | 6 | 10 | 6 | 10 | 18 | 21 | 0 | 0 | 8 | 19 | 38 | 60 |
| GTM | 55 | 40 | 55 | 40 | 110 | 80 | 0 | 0 | 0 | 0 | 220 | 160 |
| BLEED AIR | 0 | 27 | 0 | 27 | 1 | 30 | 0 | 0 | 0 | 0 | 1 | 84 |
| MAIN RED GEAR AND CLUTCH (2) | 2 | 10 | 2 | 10 | 4 | 20 | 0 | 0 | 0 | 0 | 8 | 40 |
| SHAFTING AND BEARINGS | 1 | 1 | 1 | 1 | 4 | 2 | 0 | 0 | 0 | 0 | 6 | 4 |
| CRP | 1 | 6 | 1 | 6 | 4 | 12 | 0 | 0 | 0 | 0 | 6 | 24 |
| MAIN FUEL OIL | 4 | 12 | 4 | 12 | 4 | 24 | 0 | 0 | 0 | 0 | 12 | 48 |
| MAIN PROP LUBE OIL | 4 | 5 | 4 | 5 | 6 | 12 | 0 | 0 | 0 | 0 | 14 | 22 |
| FRESHWATER TANK AND PUMPS | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 5 |
| SEAWATER SERVICE | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 4 |
| WASTE HEAT BOILER HEATING | 0 | 0 | 0 | 0 | 2 | 8 | 0 | 0 | 0 | 0 | 2 | 8 |
| SEWAGE TRTMT PLANT AND WASTE DR | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 6 |
| DISTILLING PLANT | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 4 |
| COMPRESSED AIR | 0 | 0 | 0 | 0 | 6 | 8 | 0 | 0 | 0 | 0 | 6 | 8 |
| POWER DISTRIB · SHIP CONTROLS | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 4 | 0 | 0 | 1 | 7 |
| GAS T GEN PRIME MOV, SHIP SERV/EM | 0 | 0 | 0 | 0 | 0 | 0 | 33 | 24 | 0 | 0 | 33 | 24 |
| REFRIG AND AIR CONDIT PLANTS | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | | 5 |
| TOTAL | 73 | 112 | 73 | 112 | 159 | 242 | 34 | 28 | 8 | 19 | 347 | 513 |
| | 21.5% | | 21.5% | | 47% | | 7% | | 3% | | 860 | |

- Make maximum use of summary alarms
- Adopt the philosophy of management by exception
- Consider elimination of the logging functions

The following example illustrates how simplification in the monitoring system was achieved.

If the main reduction gear and shaft bearing resistance temperature elements (RTE) are replaced with temperature switches, the ship cabling can be used to create a "Summary Bearing Fault." In addition, local readout of the "hot" bearing can be accomplished as shown in figure 3.

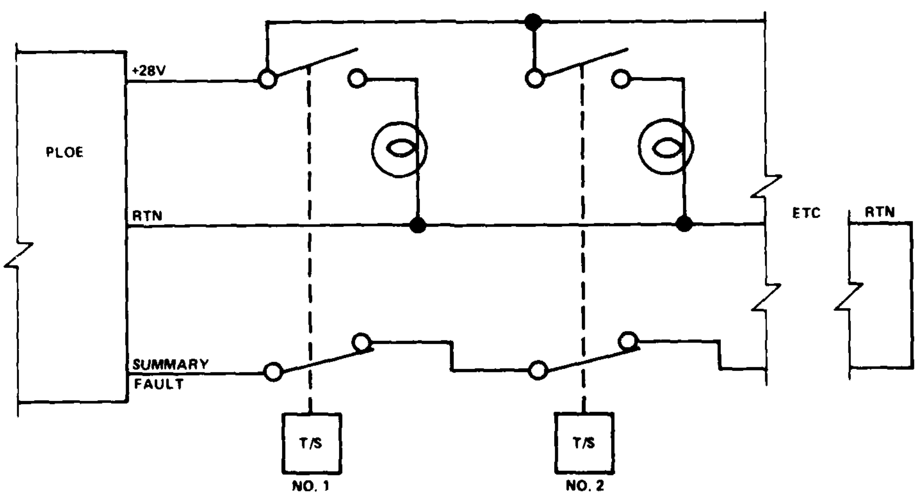
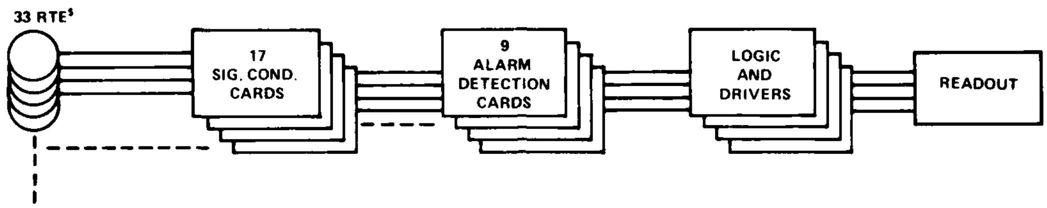


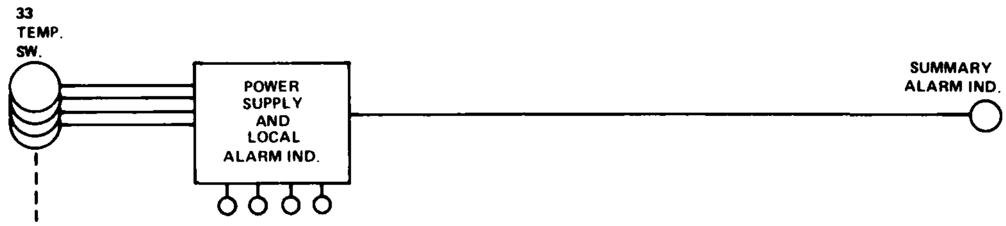

Figure 3. Bearing Overtemp Indication.

In the present system (see figure 4), a monitoring of reduction gear and shafting bearing temperature is provided by 33 RTEs together with:

- Seventeen RTE signal conditioning cards
- Nine alarm detector cards
- Logic for summarizing the alarms
- Drivers to transmit the information to the PLCC




(A) PRESENT BEARING ALARM SYSTEM




(B) PROPOSED SYSTEM

Figure 4. Bearing Alarm System (Simplified).

The technique illustrated in figure 3 would reduce the system card count required to monitor bearings by at least 26 cards per shaft. Using this technique on the Bearing Monitoring, and other monitoring systems, will greatly reduce the load on the control console without vastly affecting the maintenance-man's ability to pinpoint system problems.

Lube Oil & Other Alarms. It is proposed that the lube oil alarms be reduced from six to a single summary alarm, the CRP alarms be reduced from six to one and the fuel oil alarms be reduced from 11 to one. In the area of GTM alarms, the number of alarms can be reduced by the use of summary alarms; and if the redundant indications are eliminated, the number of nonpushbutton displays can be reduced from 41 to 17 for each GTM or from 82 to 34 for each PLOE. In the bleed air system, the need to monitor bleed air alarms for the other engine room should be eliminated. This will reduce the bleed air alarm monitoring requirement from 25 displays to eight displays.

Analog Displays. Only those analog parameters that are required for manual control will be retained. PLOE and PAMCE meters will consist of: Lube and fuel oil header pressure, GG&PT rpm, PT pressure

and temperature, power lever angle (PLA), computed torque and PT&GG vibration.

Communications. There will be (PLOE to SCC) standard order communications with the bridge and it will be of the synchro type transmitter and receiver. Except for PLA and pitch, all control elements will operate in parallel (PLOE-PAMCE). PLA and pitch commands will be transferable by the use of a rotary switch at PLOE. Integrated throttle transfer between PAMCE and SCE will be mechanized as it is in the DD system.

Signal Conditioning. The reduction of the number of analog parameters will make it possible to eliminate the engine room signal conditioning enclosures and perform all signal conditioning functions in the PLOE consoles. The use of summary alarms and the subsequent deletion of excess circuitry has provided enough space in the PLOE Console to house the required signal conditioners.

Power Supplies. Another area of savings investigated was the power supplies. If the 150 vdc uninterrupted power supply (UPS) battery system were replaced with a 28 vdc system with each station supplied with its own UPS battery array (to reduce long line losses), cheaper power supply modules could be purchased "off the shelf". An additional power cost saving can be realized by replacing the console illuminated push button (IPB) switches with toggle switches utilizing light emitting diode (LED) status indicators. The toggle switches are less costly than the IPBs and the LEDs consume much less power than the incandescent lamps used in the IPBs.

## SUMMARY OF RESULTS

The deletion of some analog signals, deletion of automatic functions, simplification of control transfer from PLOE to PAMCE, and the use of summary alarm makes it possible to delete 73 PC cards from the basic DD PLOE card count of 178 cards. Modification of the "Monitoring" requirements reduces the S/CE card count from 106 to 27, a net reduction of 79 PC cards. The remaining 27 S/CE cards can be housed in the PLOE Console thus eliminating the S/CE. If the logging requirements are eliminated for both the bell and alarm, and the S/CE No. 1 signal conditioning required for EPCE is housed in EPCE (EPCE has a spare card cage), the complete PAMISE can be eliminated. This would then require the operators to keep a hand-written log as has been and is being done on other ships. There would be no demand display available, all analog values would be displayed on meters or eliminated.

This minimal system would result in a reduction of 101 PC cards from the basic PAMCE card count of 234 cards.

The SCE would also have a reduction of PC cards as the conversion of the Standard Orders to a synchro system would eliminate the SCC's dependence upon the serial data system. Readouts of shaft rpm and propeller pitch would be changed from the present digital readout to analog meter readouts. This would also apply to any bridge wing or combined indicator panel readouts required. The SCC's dependence upon its own power supply for the propulsion system readouts, control or requests would be eliminated. All propulsion parameter power that would be required would be supplied by PAMCE or PLOE. These changes would delete 20 PC cards from the SCE. Thus, almost all SCC PC cards associated with the propulsion are eliminated.

For the propulsion system as a whole, the minimal system would reduce the card count from 934 PC cards to 470 PC cards (see table 3) and eliminate two signal conditioner enclosures and CISE in total. The impact on the PLOE in terms of controls displays and alarms is summarized in table 4. Similarly, the impact on the PAMCE is shown in table 5.

Table 3. PC Cards Summary Comparison.

| UNIT | DD | SIMPLIFIED CONTROLS ALONE | SIMPLIFIED CONTROLS + DISPLAYS | PERCENT DECREASE |
|---|---|---|---|---|
| CISE | 102 | 102 | 63 (-39) | 38 |
| S/CE | 106 | 106 | 27 (-79) | 75 |
| PACC/PAMCE | 234 | 190 (-44) | 133 (-101) | 43 |
| PLCC/PLOE | 178 | 158 (-20) | 105 (-73) | 41 |
| SCC | 30 | 30 | 10 (-20) | 67 |
| SHIP | 934 | 850 (-84) | 470 (-464) | 50 |
| | | -9% | -50% | |

Table 4. PLOE Simplification.

| FUNCTION | CONTROLS | DISPLAYS | ALARMS |
|---|---|---|---|
| GTM | 31 (-8) | 82 (-48) | 36 (-16) |
| THROTTLE | 4 (0) | 4 (-1) | 6 (-5) |
| MAIN RED. GEAR | 7 (0) | 6 (-1) | 5 (-2) |
| CRP | 2 (0) | 4 (-1) | 6 (-5) |
| SHAFT AND BRNG | 0 | 0 | 3 (-2) |
| FUEL OIL SERVICE | 8 (-2) | 27 (-22) | 11 (-10) |
| LUBE OIL SERVICE | 8 (-2) | 10 (-3) | 6 (-5) |
| EOT | 13 (-13) | 17 (-17) | 0 |
| BLEED AIR | 17 (-7) | 20 (-10) | 25 (-17) |
| | 90 (-32) | 170 (-93) | 98 (-62) |
| | -36% | -55% | -63% |

Table 5. PAMCE Simplification.

| | CONTROLS | DISPLAYS DISCR. | DISPLAYS METERS | ALARMS |
|---|---|---|---|---|
| MIMIC | 36 (-10) | 74 (-8) | 14 (-0) | 60 (-46) |
| ENG NO. 2 PANEL | 23 (-3) | 7 (-7) | 13 (-8) | 72 (-52) |
| ENG NO. 1 PANEL | 23 (-3) | 7 (-7) | 13 (-8) | 72 (-52) |
| AUX BLEED AIR PANEL | 8 (-0) | 8 (-0) | 2 (-0) | 86 (-10) |
| ENG NO. 2 DEMANDS | 16 (-6) | 11 | 2 (-2) | 11 (-1) |
| EOT PANEL | 33 (-9) | 22 (-13) | 12 (-8) | 2 (-2) |
| ENG NO. 1 DEMANDS | 9 (-5) | 11 (-5) | 3 (-2) | 1 (-1) |
| BLEED AIR CONTROL | 37 (-16) | 0 | 1 (-1) | 0 |
| | 185 (-52) | 140 (-40) | 60 (-29) | 304 (-164) |
| | -28% | -29% | -48% | -54% |

Multiplexing

The subject of hard wired versus multiplexed transmission of data cannot be treated here in the detail it deserves. However, it warrants consideration as a means for achieving simplification of intercompartment wiring and cabling.

SUMMARY AND CONCLUSIONS

It has been the general trend, recently, to increase the degree of automation in power plant controls, taking the operational burden from the operator and assigning him to managerial and supervisory tasks. This trend has resulted in some loss in capability of the operator, when faced with emergency situations, requiring fast nonautomated reactions. In this study, an approach to simplification was examined based on reduction in automatic functions and of monitored parameters. The additional effort required as a result of reduced automation would serve to maintain operator control proficiency, while the reduction in displayed parameters would serve to counterbalance the increased manual effort. Analog sensors and displays were replaced by discreets, where possible, and the use of summary alarms and displays was emphasized.

The results indicate that:

- A decrease in the order of 50 percent may be achieved in the quantity of printed circuit cards associated with a shipset of propulsion control equipment (see table 3)
- Controls, displays, and alarms are similarly reduced (see tables 4 and 5)
- The Signal Conditioning Enclosure can be virtually eliminated.

- System availability should be enhanced because of improved reliability and maintainability as a result of fewer components

- Console manning would not be affected

The approach investigated shows promise. Further examination of the impact of implementation of the approach will establish the degree to which this promise can be fulfilled.

# A NEW SHIP CONTROL DESIGN CRITERION FOR IMPROVING HEAVY WEATHER STEERING

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ABSTRACT

Conventional ship autopilots are generally designed to maintain a gyrocompass heading with minimum rudder activity. The advent of high fuel costs has initiated considerable interest by ship operators in new autopilots that hold the potential for reducing propulsive losses due to steering.

This paper presents the results of work on formulating a new steering design criterion based on minimizing the added resistance caused by rudder activity and hull drag of inertial origins caused by periodic yawing of a ship in a seaway. Quantitative evaluation of both empirical approximations to added resistance due to steering and theoretical expressions are made using nonlinear force derivatives from the surge equation. Performance criteria to which the steering control system can be designed are then developed.

Ship response with a conventional controller is compared to that with a new controller design based on minimizing propulsive losses. The performance is evaluated using nonlinear time-domain simulation of ship, steering system, and seaway. The new controller design shows interesting results; not only minimizing the added resistance arising from possible self-oscillations at the natural frequency of the ship/steering system, but also minimizing the added resistance caused by external seaway disturbances. In cases shown, significant reduction of resistance compared to that resulting from use of a conventional autopilot is achieved.

INTRODUCTION

Among the overall objectives of the Maritime Administration is the goal of improved efficiency of ship, bridge, and propulsion systems and procedures in an effort to enhance the economic position of U.S. flag ships.

One program which was initiated to attempt to achieve, in part, this goal was aimed at developing and demonstrating the utility of improved steering control for merchant ships (Reference 1).*

The goal of the program was to develop design methodology for an autopilot that would provide effective steering control with associated cost savings for a full range of seaway and stability conditions which would be applicable to a wide range of ships using the Sea-Land McLean (SL-7) as the model. This paper describes the results of the program to date.

The development of modern control theory has increased our latent ability to optimize the performance of ship steering systems. However, the full utilization of this ability requires objective and realistic definitions for optimum steering performance. Research on this aspect of the steering problem has lagged somewhat behind other aspects, and we have reached the point where further progress will require a greater emphasis on the economic, as opposed to the purely technical, questions.

From the points of view of the naval architect, the engineer, and the ship operator, the main objective of controllability research is to find the relationship between design and performance, in order to provide a basis for optimum design. The objective is quite simple. But performance implies a system of utilities, and utility of ships' autopilots has not been considered in the design of the autopilots in the past. Controllability has been the design goal for ships' autopilots.

The introduction of new forms of steering (such as "adaptive" autopilots) has posed a problem of conflict for the ship operator. Available for trade-off are the economic benefits claimed by manufacturers as opposed to actual benefits on specific ship types, trade routes, and modes of operation. Claims by the manufacturers range from 1 percent to 3 percent in fuel savings. However, the literature is sparse with regard to any conclusive data. Several ship operators are attempting to conduct evaluations on a small scale basis. The results are scattered, as would be expected, and do not offer any degree of confidence for adoption by other operators.

There have been many general claims and loosely defined utilities for such systems to date. The words "adaptive" and "optimal" appear frequently in the literature relating to steering control without meaningful definition of either. What is the rationale for an adaptive autopilot and in what regard is its performance optimal?

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*The content of this paper is based entirely upon work conducted under United States Maritime Administration Contract MA 2-4328. The material is presented by permission of the United States Maritime Administration, National Maritime Research Center, Kings Point, New York 11024.

It is the purpose of this paper to state the utility of an autopilot designed to optimize a performance criterion of propulsion losses due to steering both in terms of economic benefits and in terms of the degree to which human judgment may be removed from steering control of ships.

## THE NATURE OF THE PROBLEM

Present opinion desires that a minimum of propulsion losses be adopted as a criterion for autopilot efficiency; while controllability of the ship under automatic steering is, of couse, mandatory.

How, then, was a relationship to be found between cost savings and steering control? And how was a measure of effective, or efficient, steering controls to be determined? If both of these could be defined, could a steering controller be designed which maximized these effects? This is a general statement of the problem, but one which is far removed from even a qualitative statement, let alone its quantitative definition.

The quality of steering to this point, has been, at best, a highly subjective intangible. There is an understandable tendency to consider "good" steering to be that which holds the ship to a tight course. And this, indeed, may be the only measure of steering available to operating personnel. As long as means of adjustment of autopilot controls are available to the operator, and as long as heading error from the course recorder is the operator's only measure of steering, it is certain that the operator will adjust the controls to achieve best steering by the one measure he has - minimum heading error.

It has been understood for some time, of course, that efficient heading performance may not be compatible with efficient propulsion. And some creditable attempts have been made in the past to define a measure, or index, of relative steering efficiency of autopilots based on propulsion losses. But whatever their relative merit as measures of steering efficiency, it is certain that, to this point in time, a steering controller has not been configured which does minimize propulsion losses.

Several attempts at design of "adaptive" autopilots have been made, with associated claims as to their fuel saving ability. But it is only fair to point out that a statement of adaptivity in itself does not solve the problem of improved steering efficiency. And, in general, it is necessary to define the problem before a solution is attempted.

This, then, is the first problem - to define the problem. If, and when, the problem of improved steering efficiency can be defined in quantitative terms, i.e., if a quantitative statement of propulsion losses due to steering can be derived, then a solution may be attempted by design of a controller which minimizes these losses. And, if the need for adaptivity of that controller to maintain optimal efficiency (minimum propulsion losses) in the face of changing environmental conditions or ship characteristics, is shown, then, and only then should adaptive control techniques be investigated.

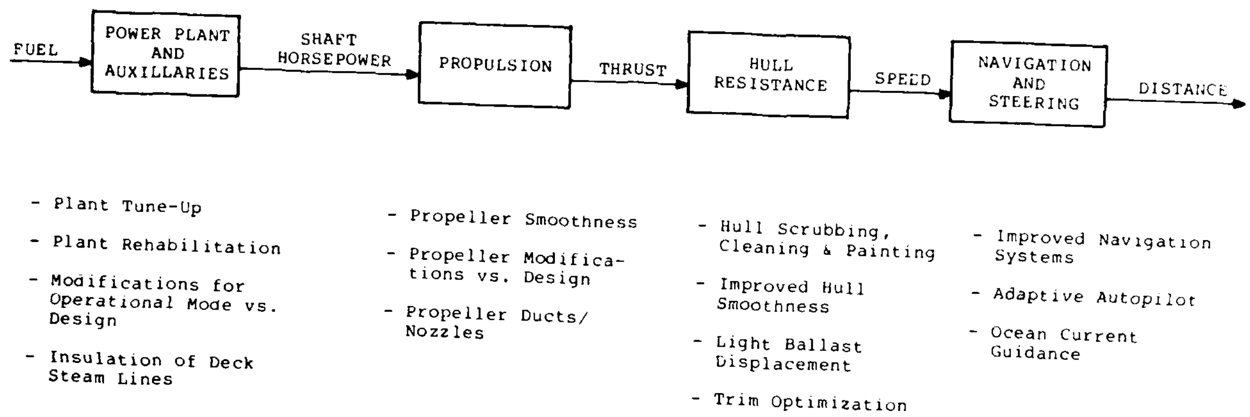


Figure 1. Potential Fuel Saving Areas on Existing Steam/Diesel Tankers

Reference 9 indicates that excess distance traveled by a high speed cargo liner, which may suffer from excessive yawing in quartering seas, will not normally exceed 0.2 percent of the nominal; while it seems clear that navigation uncertainties resulting in course errors will not cause excess distance traveled to exceed more than around the same figure from the nominal.

It is clear that neither yawing amplitudes about mean heading nor heading bias errors can be neglected in specification of a performance criterion for a steering control system for the open seas. The latter may be bounded by use of an integral control term in the steering control system, and by corrections based on the results of moderate accuracy navigation aids' position fixes; consideration of the former should form an upper bound on the magnitude of permissible yawing deviation resulting from whatever steering criterion is selected.

A more important potential source of propulsion losses, however, is excess power consumption per unit distance caused by the added resistance due to the steering. Added resistance due to steering forms the basis of the primary performance criterion adopted in the design of the steering control system for open seas course-keeping.

In this regard it is important to distinguish between total added resistances, or propulsion losses, of a ship sailing on a "straight" course, and those losses attributable to, or caused by, the steering control system. Reference 9 lists the following sources of added resistance, and indicates the respective degrees of importance of each:

SUMMARY OF ADDED RESISTANCE, OR PROPULSION LOSSES, ON "STRAIGHT COURSE"

| | |
|---|---|
| xA) | Increased wind resistance of superstructures |
| xB) | Increased hull resistance due to incident wave reflection |
| C) | Increased hull resistance due to seaway |
| xD) | Varying hull resistance due to pitching |
| +E) | Varying hull resistance due to rolling |
| x+*F) | Added resistance due to sideslip or drift |
| X+G) | Varying added resistance due to coupled yaw/sway |
| x+H) | Induced rudder resistance |

---------------

| | |
|---|---|
| x | Dominant Effect |
| + | Relevant to Steering |
| * | Small |

ISSC Spectrum*

$$\tfrac{1}{2}a^2(\omega) = \left(\frac{172.8\,H_s^2}{T_s^4\,\omega^5}\right)e^{-\frac{691}{T_s^4\,\omega^4}}$$

Beaufort (8)

$$\left.\begin{array}{l} H_s = 15.9 \text{ ft.} \\ T_s = 8.4 \text{ sec.} \end{array}\right\}*$$

Pierson-Moskowitz

$$\tfrac{1}{2}a^2(\omega) = \left(\frac{8.45}{\omega^5}\right)e^{-\frac{9.7\times10^4}{V^4\omega^4}}$$

$$H_s^2 = 3.5\times10^{-4}\,V^4$$

Beaufort (8)

$$H_s = 15.9 \text{ ft.}$$

$$\rightarrow V = 29.15 \text{ Knots}$$

(Equivalent wind velocity for partly-developed sea)

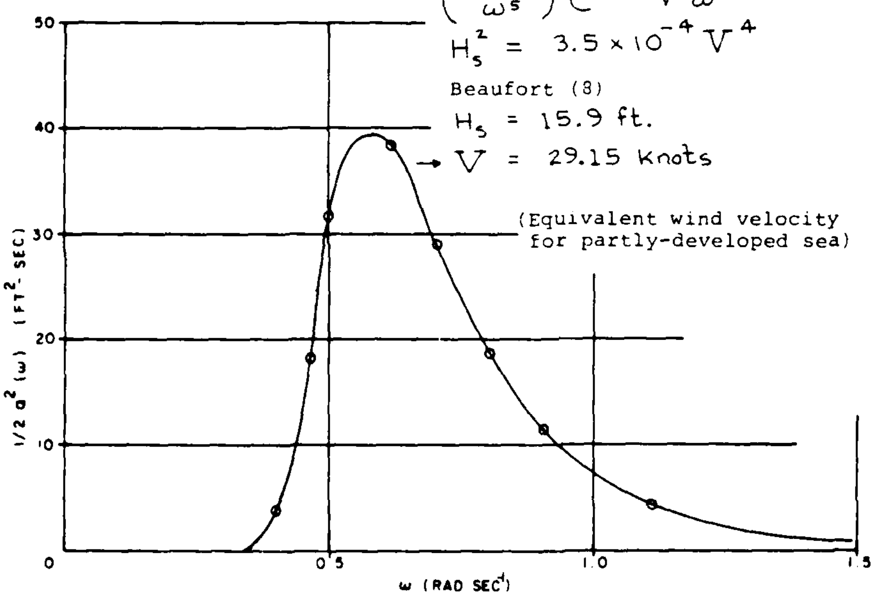


Figure 3. ISSC Spectrum for Beaufort 8
Sea in the North Atlantic

across the North Atlantic, was as follows. First, the seaway was assumed to be unidirectional, resulting from the linear superposition of elementary sinusoidal waves, the amplitudes of which were determined from the postulated seaway energy spectrum (described below), and with random phase angles, determined from a uniform probability distribution to represent an irregular sea model.

The sea spectrum used to determine the wave amplitudes in such a model was the International Ship Structure Congress (ISSC) spectrum. The ISSC spectrum is a modification of Bretschneider spectrum, and like the latter, permits observed significant wave height and period data to be used in the determination of the resulting spectrum (Reference 16). Such data was available for the North Atlantic, as reported in Reference 17, so that the ISSC spectrum appeared well suited to this particular situation (Reference 16). Data collected for a Beaufort 8 sea, as reported in Reference 18, was fitted to the ISSC spectrum in Figure 3. The equivalent wind velocity for the observed significant wave height was evaluated (Reference 16), and the resulting Pierson-Moskowitz spectrum was also shown in Figure 3; it was evident that the resulting spectrum closely fit the ISSC spectrum. For purposes of analysis, this spectrum was discretized into 25 component waves.

The summation of each of these disturbance components was of the form

$$X_{ws} = X_1 a_{ws} \cos(\omega_e t + \varphi) + X_2 a_{ws} \sin(\omega_e t + \varphi) \qquad (1)$$

each with a different random phase angle one to another, over the discretized seaway spectrum resulting in a model of an irregular seaway, such as postulated, to be used in a time-domain simulation of the system, to determine its performance in a seaway in a simulated real time.

FORMULATION OF PERFORMANCE CRITERION

The power lost in steering is attributable to excess distance sailed, and excess power consumption per unit distance. The former results in excess distance sailed of roughly one percent for a yawing amplitude about the mean heading of some 12 degrees (Reference 9); the excess distance due to a heading deviation (course error) is a factor (1-cos ) of the nominal distance.

HEADING DEVIATION (COURSE ERROR)

| HEADING DEVIATION (Degree) | EXCESS DISTANCE (Percent) |
|---|---|
| 1 | 0.015 |
| 2 | 0.06 |
| 5 | 0.38 |
| 10 | 1.54 |

Gyrocompass Kinematics and Dynamics

The gyrocompass installed aboard the SL-7, and which provides the heading reference to the automatic steering system, is the Sperry Mk 227 Gyrocompass®

The Mk 227 Gyrocompass consists of a two-axis gyro-stabilized binnacle pendulously mounted inside a set of gimbals. The gimbal order, inside-to-out, is azimuth, roll, and pitch. The compass therefore does not measure heading angle of the ship with respect to North in a true azimuth plane. True azimuth is output from a fully stabilized gyrocompass with a gimbal configuration, inside-to-out, of azimuth, pitch, and roll.

Analysis was carried out to calculate the deviation of the compass output from the mean heading of the ship due to gimbaling kinematics, when the ship is subjected to pitch and roll in a seaway. For the expected motions of the SL-7 in Beaufort 8 irregular seas at 32 knots, the approximate amplitude of heading error resulting is less than 0.25 degrees.

In addition to the effects of gimbaling dynamics on compass output (a kinematic effect), the stabilized element of the gyrocompass is subjected to dynamic effects. Pitching and rolling motions of the ship cause translational accelerations to be experienced by the stable element of the compass when the latter is situated at other than pitch and roll center axes. Analysis of this effect for worst case pitch and roll motion of the ship, with 50 feet lever arm for both pitch and roll, showed that a negligible steady-state compass error resulted.

Seaway Model

Once the ship and steering dynamics had been well defined, there remained the problem of determining a suitable representation of the external disturbances imparted to the ship by the sea, before the system's performance in a seaway could be evaluated.

The derivation of forces and moments on the hull arising from a wave of given amplitude and frequency was accomplished by the strip method of integration along the length of the hull, following References 4, 5, and 14 . Consideration was taken not only of buoyancy forces but also of those forces rising from wave orbital velocity and acceleration in derivation of the sway force and yaw moment acting on the hull by the action of the wave (References 4, 5, 6, and 15).

A correct model of the seaway itself was essential to be representative of modeling forces and moments exerted on the ship. Reference 16 contains an explanation of what a sea comprises, and how a predicted or observed sea state can be analyzed to determine the forces and/or motions of a body in that sea. The technique employed to describe the seaway applicable to operation of the SL-7

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®Gyrocompass is a registered trademark of the Sperry Rand Corporation.

Steering System Model

The SL-7 is fitted with an electrohydraulic steering system. This system is basically a closed-loop mechanical servomechanism. The actual units consist of a constant-speed variable-stroke hydraulic pump which discharges oil to a hydraulic actuator. The actuator on the SL-7 consists of hydraulic rams which can rotate the rudder through a tiller arrangement. The steering gear control device consists of a differential which receives a command signal from the helm, and adds that signal to a negative feedback signal from the rudder (rudder position). The error signal produced by the differential is in turn transmitted to the constant-speed, variable-stroke hydraulic pump. The error signal changes the magnitude and direction of the pump-stroke, which thereby changes the rate and/or direction of discharge from the pump. This in turn changes the rate and/or direction of rudder movement. When the rudder reaches the desired helm angle the feedback signal equals the command signal which results in a zero error signal. This causes the pump to be put "of-stroke," which stops the rudder movement.

The rate of rotation of the rudder is not constant, nor does it vary linearly over the entire range of rudder travel. This is, in the main, due to pump characteristics and relation to error signal, kinematic characteristics of rams and connecting linkage to rudder stock, and setting of storage motion cams. As long as there is an error signal, the steering gear will operate to synchronize the rudder position with the command position. The basic rudder rotation rate (about 2-1/3 degrees per second) will not be attained unless the error signal reaches approximately 7 degrees. If the error signal exceeds 7 degrees, the rudder will rotate at approximately a constant rate. This represents the condition when the pump is on maximum stroke and is therefore discharging fluid at an approximately constant rate.

The nonlinear steering gear dynamic model is represented as shown in the block diagram, Figure 2. The model consists of a rotary power unit and rate-limited servoactuator.

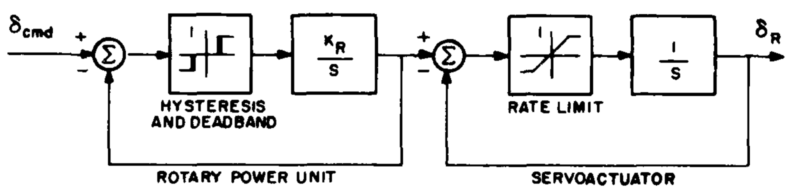


Figure 2. Nonlinear Steering Gear Dynamics

Table 1. SL-7 Characteristics

| | |
|---|---|
| Length overall | 946.6 ft. |
| Length (between perpendiculars) | 880.5 ft. |
| Breadth (max) | 105.5 ft. |
| Rudder area | 629.0 $ft.^2$ |
| | <u>Full-load</u> |
| Displacement ( $\overline{V}$ ), longtons | 47,880 |
| Draft at LCF, ft. = | 32.64 |
| LCG aft of midship ( $\overline{A}_G$ ), ft. | 39.50 |
| VCG above baseline ( $\overline{K}_G$ ), ft. | 40.91 |
| Center of buoyancy above base ( $\overline{K}_V$ ), ft. | 18.28 |
| Metacentric height ( $\overline{G}_M$ ), ft. | 4.02 |
| corrected for free liquids, ft. | 3.66 |
| Pitch gyradius $k_{yy}$ , ft. | 215.1 |
| Yaw gyradius $k_{zz}$ , ft. | 215.1 |
| Roll gyradius $k_{xx}$ , ft. | 37.3 |
| Product of inertia $k_{xz}$, $ft.^2$ | -383.0 |
| Angle of Principal Axis, deg. | -0.5 |
| Free roll period $T_r$ , sec. | 27.8 |
| Apparent gyradius $k_{xx}$ , ft. | 40.2 |
| Center of gravity above center of buoyancy z , ft. | 22.62 |
| Rudder moment-arm about CG , ft. | 27.85 |
| L/H | 27.0 |
| L/B | 8.34 |
| $A_r$/LH | 0.0219 |

Consultation with the SL-7 operators provided the following information regarding operation restrictions for the ships:

- Cruise speed up to Beaufort 8 conditions: any heading relative to wave direction

- Speed reduced to about 10-15 knots for Beaufort 10 conditions: head seas only

Normal operational cruise speed is now 23 knots, but full speed of 32 knots is attained in certain situations.

Normal ship loading can be considered basically as full-load.

## Ship Dynamics Model

The chosen method of attack on the problem of improved steering performance during open-sea course-keeping requires accurate a priori data concerning the ship's dynamics.

This method of attack was determined largely because of the availability of good hydrodynamic data for this ship and, indeed, for a wide range of merchant ships, from the Davidson Laboratory of Stevens Institute of Technology. This data, derived from extensive model tank testing, is probably the best data available on ship hydrodynamics, and has enabled the formulation of an accurate model of those ship dynamics which related to steering.

By the method of formulation, account has been taken of the important intercoupled dynamics, while, at the same time, ensuring that the resulting equations of the ship remain tractable. Coupling between ship yaw, sway, and roll has been considered in the formulation of the ship equations of motion, and the semiempirical approach adopted in References, 4, 5, and 14 has been followed, whereby the equations of motion are developed in terms of derivatives, added masses, damping coefficients, and the like, based on experimental data. For consideration of ship motions in waves, under the action of closed-loop steering control, most of the second and highest order hydrodynamic terms have not been included in the formulation of the ship dynamic model, following Reference 5. It is to be noted, however, that both this formulation of the equations of motion of the ship, and the method of solution adopted are such that hydrodynamic nonlinearities of importance could have been readily included.

The inclusion of roll dynamic in the model, and consideration of the coupling of roll into yaw and sway and vice versa, was necessitated by the long roll period and low roll damping ratio of the SL-7.

The principal dimensions and physical parameters of the SL-7 are listed in Table 1.

The factors influencing system dynamics included:

- The ship's operating envelope, i.e., the combinations of load, speed, and environmental conditions under which the ship operates
- The dynamics of the ship
- The dynamics of the steering system
- The dynamics of the ship's heading sensor, i.e., gyrocompass
- The dynamics of the seaway

Ship Operating Envelope

Preliminary to the design and evaluation of the candiate steering controllers, the ship operating envelope must be specified. The envelope encompasses those combinations of load, speed, and environmental conditions for which the adaptive control system is defined. The operating envelope for the SL-7 has recently been modified (by a reduction in operational cruise speed) to reflect fuel conservation requirements. The impact of a speed reduction on the magnitude of the steering control problem is as follows.

The cruise speed of a ship determines the possible bandwidth of seaway disturbing forces to which the ship may be exposed. This is a direct result of the effect of velocity on the seaway encounter frequency. High-speed containerships encounter the seaway over a large range of frequencies as the sea direction changes from head to stern. For the SL-7 in heavy seas at high speed, the encounter frequency with those waves containing the bulk of the seaway energy, approaches the roll natural frequency of the ship in a quartering sea, where the seaway yaw disturbance and the roll disturbance moments are significantly large. The resulting forced ship motion is correspondingly great. At lower speeds, coalescence of the encounter frequency of high energy waves with the roll natural frequency occurs essentially in a following sea in which both roll and yaw disturbing moments are reduced. The resulting disturbed ship motion is correspondingly less, although the control task of minimizing yaw dispersions is still difficult at the low encounter frequency. This emphasizes the importance of operational speed in determining the degree of difficulty of the steering control problems. While a contraction of the SL-7 operating envelope will reduce the magnitude of the steering control problem for this particular ship (still operating within the envelope), the general problem of controller design for modern merchant ships must still consider the specific control problem associated with extended operational envelopes. Consequently, the comprehensive control design method developed that specifically addressed the control problems associated with extended operating envelopes was considered the appropriate method of approach.

Irrespective of the extent of the operating envelope, the size and configurations of many modern merchant ships, such as container vessels and LNG carriers, results in relatively low roll natural frequencies so that coupling between yaw control and roll dynamics should be considered in the controller design procedure.

the ship's trade route in the North Atlantic (References 17, 18);

2. Performance criteria for added resistance due to steering were qualitatively derived and quantitatively evaluated from the relevant nonlinear force deviations of the surge equation (References 4, 5) and from the approximation for added resistance suggested by Norrbin (Reference 9). These alternate forms of a performance criteria for added resistance due to steering formed the basis for steering control system design, for evaluation of resulting performance in terms of added resistance, and for assessment of the accuracy of the approximate form of the performance criterion;

3. Candidate controllers were designed to minimize these performance criteria at various design conditions of the ship's operational envelope. Since the seaway disturbances on the ship are neither deterministic nor of a Gaussian stochastic nature, controller design techniques employing both parameter optimization in the frequency domain (References 21, 22) and the linear quadratic Gaussian (LQG) method of control system optimization (References 23, 24, 25) were attempted to minimize added resistance due to steering;

4. Resulting performance was evaluated using a nonlinear time domain simulation of ship, steering system, and seaway. Optimum control parameters which minimized added resistance at various ship speeds and seaway conditions were found on a iterative basis using the techniques of 3) above, by means of this simulation.

   By this means, optimum control parameters were defined over the ship's operating envelope, and the resulting performance in terms of both yaw deviation and added resistance evaluated;

5. A strategy was defined for automatic adaptivity of control system parameters to changing ship characteristics and environmental conditions such that on-line minimization of added resistance and acceptable bounded heading performance of the ship resulted.

## SYSTEM DYNAMICS

Before a solution to the problem of improved automatic steering efficiency in the open seas could be attempted, it was essential that an accurate model of the system dynamics affecting steering performance be formulated.

The bandwidth of the closed loop response should be as wide as practicable, in order that the necessary steering activity, even when aperiodic, may occur in the highest-possible frequency range because hull losses are inversely proportional to steering frequency with given rudder amplitude.

The necessary steering corrections should be executed as early as possible with the smallest amplitude possible.

When this has been achieved in practice, it is suprising to see how the aperiodic nature of the system restrict the number of rudder operations even in spite of wide bandwidth.

Now, Bech followed, in his work, much of the work upon which the work of the present program is based, namely that of Nomoto and Motoyama, Eda and Norrbin. As will be seen, his recommendation for controller design, is exactly opposite to that found to be optimum for the SL-7. And, at first sight, a high high bandwidth controller to achieve a minimum of propulsion losses would seem hard to defend.

To summarize, the situation at the present time is that, in spite of some creditable attempts to define a measure, or index, of relative steering efficiency of autopilots based on propulsion losses, and of some general recommendations for the design of an autopilot which minimize propulsion losses (many of which conflict with one another) a steering controller has not been configured which does minimize propulsion losses.

METHOD OF ATTACK

This paper outlines the design methodology for an automatic ship steering control system to minimize propulsion losses due to steering.

The method described uses state-of-the-art knowledge of ship and seaway dynamics and of control design techniques to develop an objective and rigorous approach to problem definition and solution. It is based upon the solid base of Eda's work (References 4, 5, 8) and uses the concepts of Nomoto and Motoyama (Reference 3) as developed by Norrbin (Reference 9). No gross assumptions regarding ship's motions are made, nor is an empirical model of the ship or seaway employed in the treatment of controllability and propulsion losses due to steering.

The following general approach was taken:

1. An accurate dynamic model of the ship/steering system in a seaway was constructed, and its motion and added resistance due to steering calculated. The ship model was based upon linearized equations of motion (Reference 4) using experimentally measured hydrodynamic coefficients, for the SL-7 high speed containership. The seaway was modeled as an irregular sea (References 14, 16, 18) using data taken from

expression "added resistance due to steering." Norrbin did go on, in that paper, to derive an empirical performance index of steering efficiency based on an approximation to added resistance arising from, again, assumptions regarding the ship's motion under the action of automatic steering. Norrbin's form of performance index is of great practical importance and does form a basis for control system design carried out in the present program.

The nature of these frequently mentioned assumptions regarding ship's motion and added resistance due to steering should be explained at this point. The contribution to drag (or thrust) of the hull of inertial origin is proportional to the magnitudes of yaw rates and of sway (the lateral translational velocity of the ship) and to the phase relationship between these motions. The following assumptions have been made by many workers in the area:

1. The ship exhibits relatively long-term self-excited oscillations emanating from the steering system;

2. These oscillations occur at the "natural frequency" of the ship/steering system, claimed to be around 100 to 200 seconds;

3. The yaw rate and sway motions are in phase with one another during such oscillations. Thus the hull inertia will always result, in this situation, in an increase in resistance of the vessel;

4. The ship will behave as in maneuvering, rotating about its turning pivot center during such closed-loop oscillations;

5. The added resistance due to self-oscillation induced by rudder actions is of major importance compared to that due to external disturbances from the seaway. Certain seaway conditions are such, in fact, that yaw rate and sway motions are in quadrature, resulting in no increase in resistance.

An obvious implication of these assumptions would seem to be, to minimize propulsion losses:

a) Minimize added resistance due to low frequency oscillations by designing to a performance index based on Norrbin's (Reference 9);

b) Provide attenuation of seaway disturbances effects by employing a low bandwidth controller.

And almost all workers have drawn these conclusions, with one notable exception. Mogens Bech, whose innovative approach to the problem of ship motions and maneuverability, particularly with relation to directionally unstable hulls (Reference 10 and 11), commands much respect, published a paper in 1972 (Reference 12), where he considered the nonlinear effects of both ship and steering system in more detail than had been before attempted. The paper treated the problem by classical control system techniques in the frequency domain. Bech's conclusions, however, in that paper were:

of automatically steered ships, but did define the mean resistance suffered by the ship under automatic control. Effects of variation in steering system parameters were explored on an analytical basis.

This paper by Eda remains by far the most analytically rigorous in the definition of the problem of steered ships in terms of controllability and added resistance. And, together with the earlier paper (Reference 4) of which he was joint author, it offers the means to attack the problem by enabling formulation of the ship hydrodynamics on a linear basis, with the means to evaluate the coefficients of the equations, i.e., the problem is shown to be tractable, other than on a trial and error basis.

Eda's work in this area formed the basis of much of the work carried out in the present program.

Meanwhile, other papers attempted a defintion of the problem and its solution.

Motora, in 1967 (Reference 7), and Motora and Koyama, in 1968 (Reference 8) published papers on the subject. These papers, while of historic importance, have little to offer to the problem seen in hindsight. Oversimplification of the ship model, and a quick reversion to empirical techniques led, in fact, to the derivation of a performance index for steering, which, while undoubtedly having merit inasmuch as it did provide a measure of relative steering quality of ship's autopilots which was experimentally verified at sea, did not accurately reflect, even on an empirical basis, propulsion losses due to steering. They did, however, as already stated, lead to some overall improvement in autopilot control settings to achieve "better steering" in a qualitative sense. For this reason, they may be regarded as an important contribution to the problem in, and of, their time.

The penalty in terms of distance travelled, and therefore of propulsion losses, caused by either yawing of a vessel or by course errors, is extremely small in relation to other efforts, unless these have a magnitude of the order of 10 degrees. (The steering performance index formulated by Motora and Koyama (Reference 8) was composed by a term related to excess distance and one due to rudder drag; the important contribution due to yawing and swaying of the hull was not included.)

It is relevant, at this point, to comment upon the earlier assertion (Reference 2) that fuel savings can be achieved by improved navigation. These potential savings accrue from maximum use of available data on winds and ocean currents. For this knowledge, planning of routes can be made to take maximum advantage of these effects. Better navigation is required to follow such planned routes with precision. There is little to be gained by holding a tight, accurate course from point A to point B, per se. And such may well conflict with the requirements for improved steering efficiency.

The work, by Motora and Koyama, therefore, was to some extent in conflict with that of Nomoto and Motoyama earlier. In 1972, however, Norrbin published a very important paper (Reference 9) which, while following a more rigorous approach to ship motions, did follow and build upon the work of Nomoto and Motoyama in the definition of propulsion losses due to steering, or to use Norrbin's

(2) Savings due to improved steering may be derived from extremely short term measurements. Namely, during constant ship and environmental conditions (say, over a period of some 40 minutes), the performance, in terms of horsepower or speed, of one steering system against another on the same ship can be measured.

Repeated test runs can be made over the same, and varying sea conditions, until an extensive comparison of the two systems' performance can be made both over the range of sea conditions experienced by the ship during the course of a voyage, and for the voyage overall.

Essential to both these methods is the installation of a torsion meter on the main shaft.

BACKGROUND

This, then, is the nature and extent of the problem. How then to attack it? Credit for the first attempt to analyze and quantify propulsion losses associated with steering goes to Nomoto and Motoyma with publication of a paper in 1966 - "Loss of Propulsion Power Caused by Yawing With Particular Reference to Automatic Steering" (Reference 3). This paper did define, in analytical terms, propulsion losses due to steering. Quantification of the effect, and its attempted experimental verification, suffered from assumptions made regarding the yawing motion of the ship under automatic steering. That these assumptions were incorrect may be evidenced by the principal conclusion of the paper that propulsion losses associated with steering control reach as high as 20 percent of calm water normal propulsion power. In a qualitative sense, however, the paper still ranks among the most important in its treatment of propulsion losses due to steering. Its failure to properly quantify the effects was due, in fact, to a resort to empirical relationships and data relating to ship's motions.

A landmark paper with regard to ship's motions and their treatment was published in 1965 by Eda and Crane (Reference 4), "Steering Characteristics of Ships in Calm Water and Waves."

The importance of this paper is that it consisted of an evaluation of the steering performance of ships having systematic variations of hull and appendage configuration. This was based on hydrodynamic forces and moments associated with horizontal motions of ships, as obtained by rotation-arm tests, and the application of linearized equations of motion to the yawing behavior of a ship in following and quartering seas. Here was presented the means to describe the ship's course-keeping motion by a linearized set of equations, the coefficients of which were derivable from experimental data. Since it is extremely difficult to attempt control sytem design of other than a linearized system, the method of attack of this paper provided the first means by which a proper analytical approach to improved steering control design could be undertaken. And Eda did follow this with a paper in 1971 (Reference 5) examining directional stability and control of ships in waves, particularly in following seas. The work was not only confined to controllability

Let us then put first things first: what is the problem definition? Reference 2 has specified the following areas where fuel losses occur during the operation of a ship in the open seas. The principal areas of fuel losses on existing steam/diesel tankers are summarized in Figure 1 (extracted from Reference 2), and are shown to be in four main areas:

- Power plant and auxiliaries
- Propeller efficiency
- Hull resistance
- Navigation and steering

Reference 2 goes into the enumeration of potential fuel savings in each of these areas achievable by a variety of techniques, while stating that the individual fuel savings credits for the various areas interact with each other when consideration is given to the overall potential fuel savings figures. It is sufficient for our purposes, to identify the following:

- Propulsion losses during normal operation of a ship in the open seas arise from many and diverse causes, of which one is steering

- The separation of these losses, one from another so that remedial action may be taken, is no small task. This is true in the short run, and in the long run, so that identification of losses and their correlation with a particular ship effect is only achievable with a comprehensive performance monitoring and data reduction system

- The implication for improved steering efficiency is that a criterion for these propulsion losses due to the steering system must be derived from a theoretical basis first. Candidate steering control systems may then be configured and their potential fuel savings relative to existing autopilots evaluated by analysis or simulation

- Validation of such savings accruing from improved steering control is an extremely demanding task. It is achievable by one, or both, of two methods:

  (1) Savings due to improved steering may be enumerated over a long period of time only when a comprehensive performance monitoring and data reduction operation of overall ship performance is in effect. Reference 27 provides some details of the means by which basic performance monitoring is carried out. But, when correlation of fuel savings to a given area is made, it involves much smoothing and normalization of data involving multiple regression techniques. Much work is yet to be done in this area;

Fuel consumption at sea is also affected, in large measure, by such factors as propulsion and engine performance, ballasting, trim and condition of the bottom. It is, in general, the inability to separate these losses from those due to steering, in the short term, which necessitates the use of an analytical expression for added resistance due to steering. The performance objective of the system in open-sea course-keeping was therefore formulated as minimum added resistance due to steering with the constraint of no rudder rate saturation. Thus, propulsion losses affected by steering would be minimized, while ensuring, at the same time, no loss of control due to saturation of the rudder sevoactuator (i.e., main pump).

Performance Criterion Based on True Added Resistance

Total instantaneous surge due to steering may be written:

$$\Delta X = \left(m + \frac{\rho}{2} L A X'_{vr}\right) v r + \tfrac{1}{2}\left(\frac{\rho}{2} A X'_{\delta\delta} U^2\right) \delta^2 \tag{2}$$

where (neglecting the term in $v^2$ which is small)

$m$ = mass of ship

$\rho$ = density of sea water

$L$ = ship length between perpendiculars

$A$ = $L^2$

$U$ = ship's water speed

$v$ = sway velocity of ship

$r$ = yaw rate of ship

$\delta$ = rudder angle

$X'_{vr}$ = force coefficient due to yaw/sway (+ve)

$X'_{\delta\delta}$ = force coefficent due to rudder angel (-ve)

The mean surge resulting is then

$$\overline{\Delta X} = \left(m + \frac{\rho}{2} L A X'_{vr}\right) \frac{v_a r_a}{2} \cos(\phi_v - \phi_r) + \tfrac{1}{2}\left(\frac{\rho}{2} A X'_{\delta\delta} U^2\right) \delta_a^2/2 \tag{3}$$

where

$v_a$ = amplitude of sway velocity

$r_a$ = amplitude of yaw rate

$\delta_a$ = amplitude of rudder angle

$\phi_v - \phi_r$ = phase difference between sway and yaw rate

It may be seen that the yaw/sway resistance component varies as does the phase angle between sway and yaw rate, i.e.,

yaw/sway effect

$\pi/2 < (\phi_v - \phi_r) < -\pi/2$ : resistance increased

$(\phi_v - \phi_r) = \pi/2, -\pi/2$ : no change

$-\pi/2 < (\phi_v - \phi_r) < \pi/2$ : resistance decreased

A performance criterion for control system design may then be formulated for mean added resistance:

$$J = \lim_{T \to \infty} \frac{1}{2T} \int_0^T \left\{ -\alpha v r + \gamma U^2 \delta^2 \right\} dt \tag{4}$$

where $\alpha, \gamma$ are constants, for a given loading. The accuracy of such a criterion is dependent on accurate knowledge of the nonlinear coefficients $X'_{vr}$ and $X'_{\delta\delta}$ while the criterion itself suffers from the disadvantage that it involves sway velocity, a measurement of which is not available.

Normalizing

$$J_{norm} = \lim_{T \to \infty} 1/2T \int_0^T \left[ -\lambda'' v r + \delta^2 \right] dt$$

$$\lambda'' = \frac{2\left(m + \frac{\rho}{2} L A\right) X'_{vr}}{\frac{\rho}{2} A X'_{\delta\delta} U^2} \tag{5}$$

Empirical Criterion Based on Approximate Added Resistance

A semiempirical criterion for measuring the relative performance of autopilots was developed, in Reference 9 (based on a form of criterion proposed in Reference 8), in which an approximation for hull drag of inertial origin was developed from an assumption of small amplitude oscillations around the steady-state pivot point of the ship during yawing at the ship/steering control system natural frequency

$$\left[\overline{\Delta X_{vr}}\right]_{\omega \to 0} \approx -\frac{mL}{2}\left(1+X''_{vr}\right)\frac{\overline{OP}}{L}\,\omega^2 \psi_a^2 \tag{6}$$

where

$$X''_{vr} = \frac{\rho}{2} L A X'_{vr}/m$$

$\overline{OP}$ = distance from c.g. to pivot center

$\omega$ = natural frequency of closed-loop steering control system

$\psi_a$ = yaw amplitude

Such a formulation assumed that sway and yaw rate were in phase at low (and high) frequencies of oscillation, always resulting in a hull drag. This may be extended to derive an alternative approximate criterion for added resistance

$$J' = \frac{1}{2T}\int_0^T \left[\lambda \psi^2 + \delta^2\right] dt \quad (T \to \infty) \tag{7}$$

where

$$\lambda = \frac{2m\left(1+X''_{vr}\right)\overline{OP}/L}{\rho/2\, L X'_{\delta\delta}} \cdot \frac{\omega^2}{U^2}$$

or , alternatively

$$J = \frac{1}{2T}\int_0^T \left[\lambda' \dot{\psi}^2 + \delta^2\right] dt \quad (T \to \infty)$$

$$\lambda' = \frac{2m\left(1+X''_{vr}\right)\overline{OP}/L}{\rho/2\, L X'_{\delta\delta} U^2} \tag{8}$$

It is interesting to note that while Reference 9 gives a value for the weighting factor $\lambda$ for a cargo ship of around 7, in the criterion of Reference 8

$$J = (\overline{\psi^2}) + \lambda' \cdot (\overline{\delta^2}) \tag{9}$$

where the two terms were attributed to excess distance and added resistance, respectively, then a value of $\lambda' = 8$ was given for a Mariner hull. A difference in the weightings given to yaw amplitude rudder angle of over 50 exists between the two criteria.

CONTROL SYSTEM DESIGN AND TRADEOFF ANALYSIS

These alternate forms of a performance criterion for propulsion loses due to steering (Equations 5, 7 and 8) form the basis for development and evaluation of a number of candidate steering controllers at various design conditions.

For preliminary control system design a performance criterion:

$$J = \lim_{T \to \infty} \frac{1}{2T} \int_0^T \{\lambda \psi^2 + \delta^2\} dt \tag{10}$$
$$\dot{\delta} < 2.3 \text{ deg/sec}$$

seemed attractive, based on the following rationale. It would seem that the approximation of Reference 9 could be expected to hold true for ship/autopilot closed-loop self-oscillations caused by internal nonliner effects, so that the use of the criterion given by Equation 10 with the correct calculated values of $\lambda$ would minimize yaw deviations at the natural frequency of the ship/autopilot closed-loop system. A constraint on rudder rate to ensure that it does not saturate would reduce the tendency for closed-loop auto-oscillations. to occur. Of necessity, the criterion would also constrain yaw deviations, to the extent that added resistance would be minimized. The control system resulting from the use of such a criterion could also be expected, by correct choice of system bandwidth (natural frequency), to significantly attenuate the effects of external seaway disturbance on the control system, so reducing the resistance losses results from such forced oscillations by minimizing rudder motion. This, then, was the criterion first considered in the design of candidate controllers to minimize added resistance due to steering.

Clearly, however, control system bandwidth is not the only factor which can effect a change in the yaw/sway phase relationship. For this reason, control system design to the criterion, of Equation 5, based on actual added resistance, was also carried out in an attempt to minimize propulsion losses due to steering.

Frequency Domain Synthesis and Evaluation

The performance criterion of Equation 9 for possible design of the steering control system may be written as

$$J = \int_0^{\infty} \left\{ \lambda \psi^2 + \delta^2 \right\} dt \tag{11}$$

to reflect the integral of added resistance resulting from self-sustaining or externally-induced yaw deviations and rudder actions.

The design of a control system to minimize the criterion of Equation 11 may be achieved by several means. It was decided to first minimize Equation 11 by parameter optimization in the frequency domain using a fixed-structure controller. (Reference 21 and 22).

From Equation 6

$$\lambda = \frac{2m\left(1 + X''_{vr}\right)\frac{\overline{OP}}{L}}{\frac{\rho}{2} L X'_{\delta\delta}} \cdot \frac{\omega^2}{U^2} \tag{12}$$

where $\overline{OP}/L = 0.33$. (This assumes pivot-point $P$ a little aft of the bow.) Based on the form of the encounter frequency spectrum, and on the open-loop ship dynamics, a closed-loop natural frequency of 0.05 rad/sec to filter external seaway disturbance was first attempted for the controller by setting $\omega$ = 0.05 rad/sec.

The form of the control system was:

$$\delta_c = \frac{K_1\left(1 + T_1 s\right)}{\left(1 + T_2 s\right)} \psi \tag{13}$$

a simple proportional-plus-derivative controller form, which could be implemented in either analog or digital form. The use of an integral controller for correction of steady-state errors would be achieved

$$\delta_c = \left[\frac{K_1\left(1 + T_1 s\right)}{\left(1 + T_2 s\right)} + \frac{1}{T_I s}\right] \tag{14}$$

by selecting the integral control time constant $T_I$ such that the dynamic characteristics of the controller were unaffected.

The ship typically runs in the fully-loaded condition at cruise speed. The previous cruise speed for the SL-7 was 32 knots. Both design conditions were analyzed, as was a reduced speed condition of 16 knots.

For the controller resulting from this design technique, the variation of added resistance and its components, and the empirical approximation $J$ (scaled to $\ell\ell_{r_t}$), respectively, with seaway directions, are shown in Figure 4, for speeds of 32, 23, and 16 knots. As can be seen from examination of Figure 4, the trend of $J$, approximate added resistance, as a function of encounter angle, followed that of actual added resistance, $\Delta X$ fairly faithfully, for the 32-knot case, with minimum values of each (in terms of positive surge) occurring around 30 degrees. The trend of $J$, as compared to $\Delta X$ as a function of encounter angle for the speeds 23 and 16 knots, is not quite so favorable, but the minimum of both functions remained fairly well matched (30 degrees).

It does appear that minimization of the criterion

$$J = \lambda \overline{\psi^2} + \overline{\delta^2} \tag{15}$$

does result in approximate minimization of added resistance caused by external seaway disturbance.

A further improvement in performance (in terms of propulsion losses) was achieved through use of a 0.25 rad/sec controller for the 32-knot, 30-degree encounter angle case. (This result conflicted with the work done previously (References 5, 12, 13), and clearly showed that the concept of bandwidth is of only limited value in the reduction of resistance losses of inertial origin where the phase relationship between yaw rate and sway velocity of considerable importance.)

Further reduction of bandwidth below 0.05 rad/sec, and further increase beyond 0.25 rad/sec resulted in degradation of performance across-the-board.

A requirement for adaptivity to seaway encounter angle was therefore established, albeit that the need appeared only to exist for the high speed following/quartering sea case.

LQG Controller Design

Controllers synthesized by the linear quadratic Gaussian (LQG) method were next considered. (References 23, 24, and 25).

By their very nature, LQG controllers, in general, can be expected to attempt to handle well disturbances at all frequencies, but their performance will not be optimal in other than a Stochastic Gaussian (white noise) environment.

To contrast, first the performance of LQG controllers configured to the same criterion as those synthesized by parameter optimization

i.e.,

$$J = \int_0^\infty [\lambda \psi^2 + \delta^2] dt \tag{16}$$

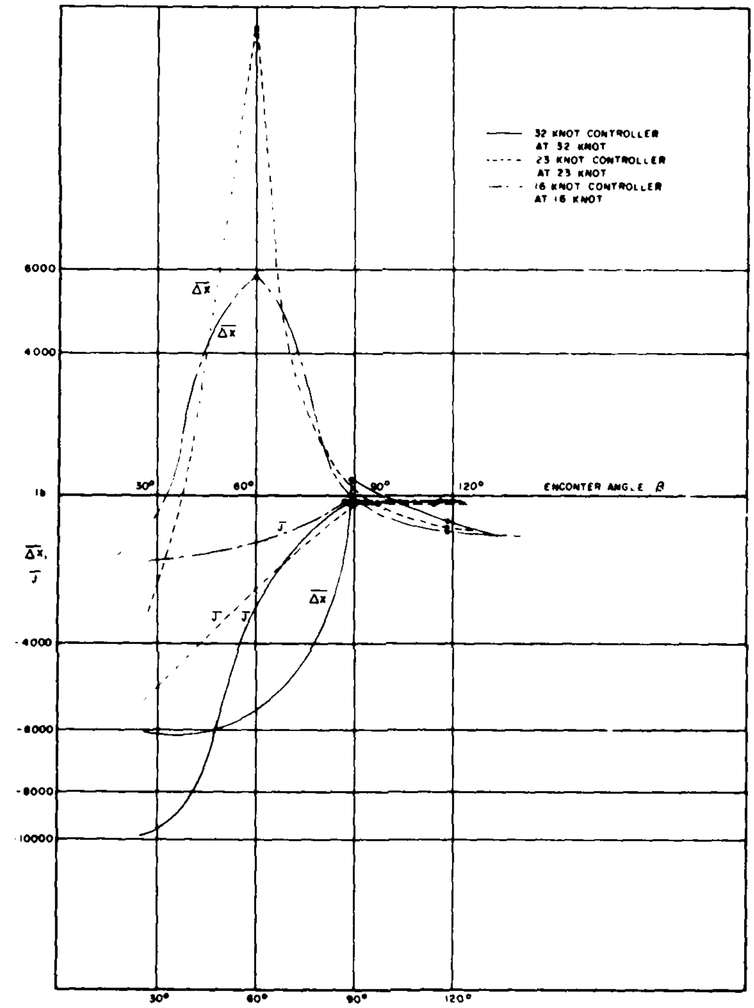


Figure 4. 0.05 Rad/Sec Controller: Added Resistance and Performance Index Versus Encounter Angle

a comparision was made of the performance of LQG resulting from the use of such a controller, with that form the lead/lag controller designed using the same weighting value of $\lambda$ (i.e., the 0.05 rad/sec bandwidth controller detailed in the preceding pages), and is shown in Figure 5, in terms of total added resistance at a speed of 32 knots. For all encounter angles of interest, the lead/lag controller resulted in significantly lower losses than the straight LQG controller. By the same token, as can be seen in Figure 6, the LQG controller exerted significantly better heading control over the vessel over the same encounter angles at 32 knots.

It may also be seen, that, for the LQG controller, minimum $J$ no longer occurred at the same encounter angle as minimum $\Delta X$ .

The controllers resulting from LQG design were full-state feedback controllers, in form, at first sight, different from classical controllers of the lead/lag fixed-structure form. But, if the feedback term involving sway velocity is neglected (due to its very small feedback gain value), then the controllers are essentially proportional-plus-rate controller similar to those obtained by use of a rate gyro with no low pass filtering applied.

A lead/lag equivalent to this controller brings about significant improvement to the straight LQG controller (Figure 5), but still cannot match the performance of the original lead/lag controller in terms of added resistance.

Considering the design of controllers taking into account the phase relationship between sway velocity and yaw rate explicitly through the use of the performance criterion based on actual added resistance, which does not explicitly require any presupposition regarding controller/ship natural frequency.

i.e., $$J = \int_0^\infty \left[ -\lambda'' v r + \delta^2 \right] dt \qquad (17)$$

where

$$\lambda'' = \frac{2\left(m + \frac{\rho}{2} L A\right) X'_{vr}}{\rho/2 \, A X'_{\delta\delta} U^2} \qquad (18)$$

where the weighting matrix (based on the lateral dynamics of the ship, sway ( $v$ ), yaw rate ( $r$ ), and yaw ( $\psi$ ) is of the form:

$$Q = \begin{bmatrix} 0 & -\lambda''/2 & 0 \\ -\lambda''/2 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

the controller resulting, for the nominal value of $\lambda''$ at 32 knots

$$\delta^{*} = 0.062\, v \quad -9.033\, r$$

with closed-loop eigenvalues in the lateral plane: 0.0
-0.0964
-0.2121

The resulting added resistance evaluated by time-domain simulation is shown, as a function of encounter angle in Figure 7 for a ship's speed of 32 knots. Performance is poorer than either of the previous controllers.

The controller is essentially a rate controller (again neglecting the feedback gain on sway) as might be expected since yaw is not penalized in the performance criterion. While this may result in a stable system for this ship, through use of integral control, it is, in general, unacceptable for the controlled course-keeping requirement of merchant ships.

For this reason, a penalty was placed on yaw, through use of a weighting matrix of the form

$$Q = \begin{bmatrix} 0 & -\lambda''/2 & 0 \\ -\lambda''/2 & 0 & 0 \\ 0 & 0 & \lambda \end{bmatrix}$$

In an attempt to find a controller which minimized actual added resistance $\Delta X$, and also to investigate the effect of control system parameters adaptivity as a function of encounter angle, then values of $\lambda$ and $\lambda''$, were varied, in the Q-weighting matrix. Figures 6, 8, 9, and 10 show salient performance as a function of encounter angle. As may be seen, no controller has performance, in terms of minimum added resistance to match that of the 0.05 rad/sec bandwidth lead/lag controller. As might be expected for this form of controller, controllability in following through beam seas, was inversely related to propulsion efficiency.

Describing Function Analysis of Steering System Nonlinearities

Investigation of the steering system nonlinearities on system stability was carried out by the describing function method of analysis.

The performance criterion for steering included the requirement that the rudder servoactuator (main pump) not saturate (i.e., pump not go on full stroke)
i.e.,

$$\dot{\delta}_{max} < 2.3 \text{ degrees/sec} \tag{19}$$

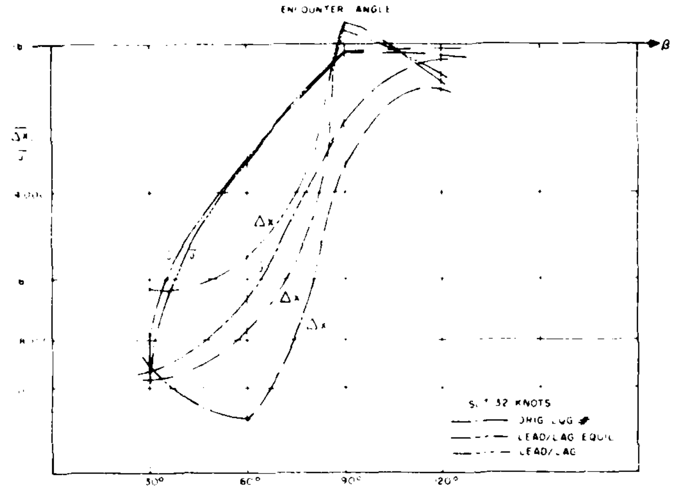

Figure 5. SL-7 - 32 Knots: Comparison of Added Resistance $\overline{\Delta x}$ and Performance Index $\bar{J}$ Performance for LQG, Lead/Lag, and Equivalent Lead/Lag Controller

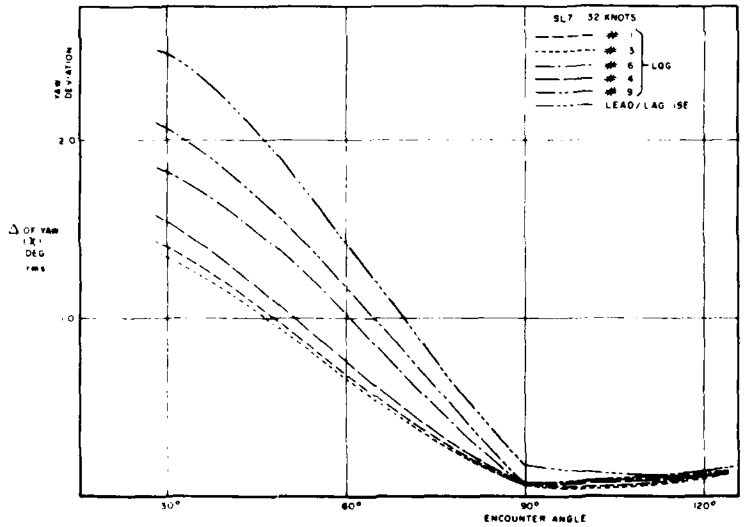


Figure 6. SL-7 - 32 Knots: Comparison of Yaw Deviation Performance for Various LQG Controller and Lead/Lag (ISE) Controller

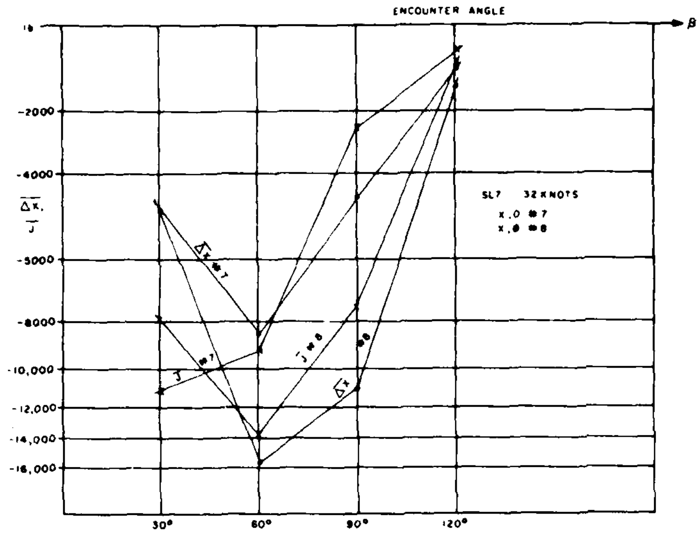


Figure 7. SL-7 - 32 Knots: Added Resistance Performance for LQG Controllers No. 7 and No. 8

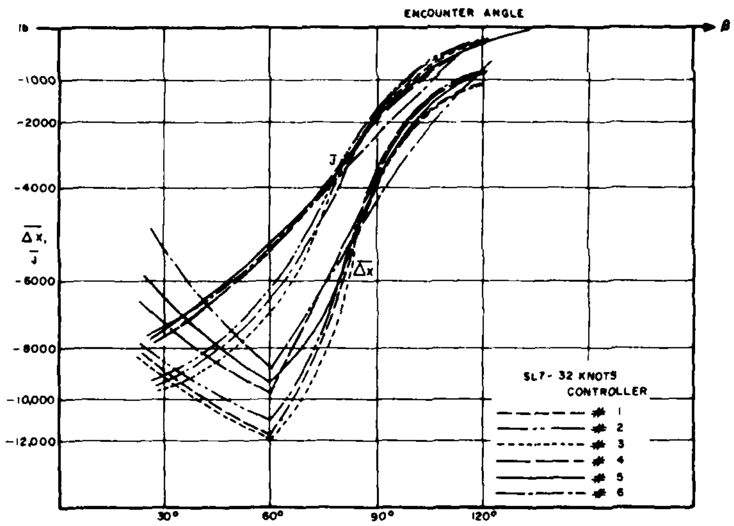


Figure 8. SL-7 - 32 Knots: Effect on Added Resistance Performance of Variation of $\lambda$ in LQG Controller

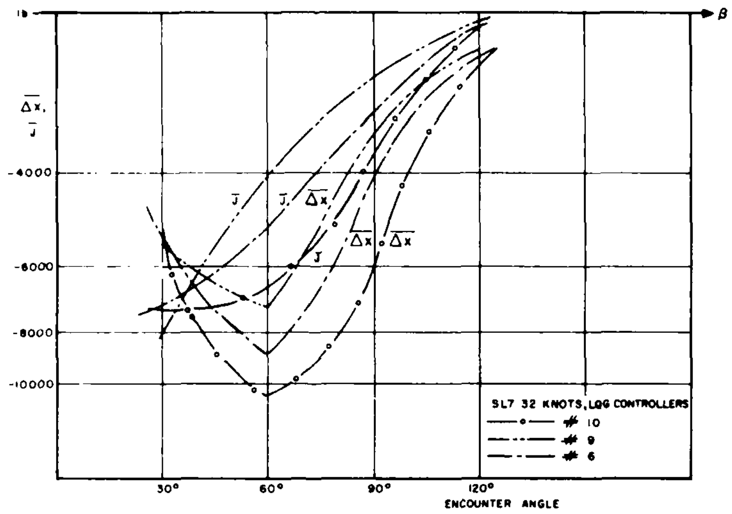


Figure 9. SL-7 - Lag Controllers - 32 Knots
Effect of Variation of $\lambda''$ on Performance
of LQG Controllers

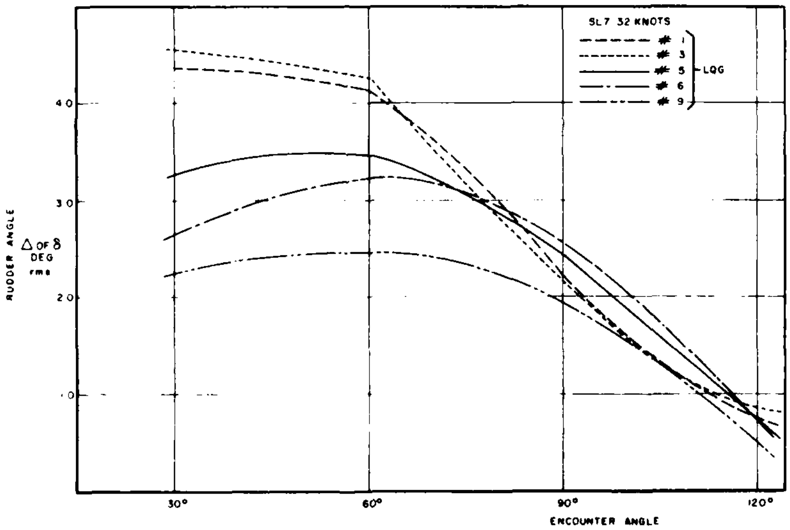


Figure 10. SL-7 - 32 Knots: Rudder Angle
Resulting from Various LQG Controllers

so, it can be assumed that the latter servo remains within its linear range during course-keeping, so that it may be modeled, for purposes of this particular analysis as a first-order lag.
i.e.,

$$\delta_a / \delta_r = \frac{1}{1 + \tau s} \tag{20}$$

with time constant $\tau$ = 3 seconds.

Investigation of nonlinear behavior may , therefore, be restricted to the Rotary Power Unit. The effect of its nonlinearities on overall system performance is analyzed by the describing function method as follows (Reference 26).

The overall ship/steering system loop may be configured as shown in Figure 11. The ship is represented as a second order model of the RPU nonlinearities by the describing function $N(x)$ as shown. A lead/lag controller is considered as shown.

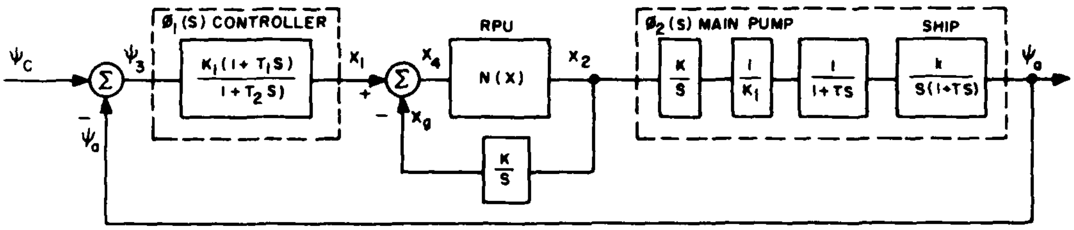


Figure 11. Nonlinear Model of Steering System

The linear frequency responsive transfer functions may be lumped into two parts: $\phi_1(\omega)$ preceding the nonlinear element and $\phi_2(\omega)$ following for the nonlinearity to the output $\psi_a$ .

If the following condition is met then, the potential for a limit-cycle exists within the system

$$\phi_1(\omega)\phi_2(\omega) + \frac{K}{j\omega} = -\frac{1}{N(x)} \tag{21}$$

The nonlinearity of the RPU, i.e., deadband and hysteresis (Reference 26), and its associated describing function is shown in Figure 12.

Table 2. Key for LQG Controller Designation

(Controller Characteristics for 32 knots)

| | | $\lambda$ | $\lambda''/2$ | $\eta$ | $K_v$ | $K_r$ | $K_x$ | CL POLES |
|---|---|---|---|---|---|---|---|---|
| Nominal | 1 | 4.2 | -2.69 | $8.2.10^{-4}$ | 0.05074228 | -17.153176 | -2.0493201 | -0.036 -0.108 -0.203 |
| | 2 | 3.2 | -2.69 | $8.2.10^{-4}$ | 0.05171189 | -16.185575 | -1.7866399 | -0.032 -0.1046 -0.2056 |
| | 3 | 5.2 | -2.69 | $8.2.10^{-4}$ | 0.04995601 | -17.996302 | -2.2803211 | -0.0393 -0.1114 -0.2008 |
| | 4 | 1.2 | -2.69 | $8.2.10^{-4}$ | 0.05485367 | -13.503726 | -1.0905607 | -0.0202 |
| | 5 | 0.7 | -2.69 | $8.2.10^{-4}$ | 0.05634 | -12.43109 | -0.8214 | -0.015 |
| | 6 | 0.1 | -2.69 | $8.2.10^{-4}$ | 0.060337 | - 9.9787 | -0.225158 | -0.0042 -0.0967 -0.2119 |
| | 7 | 0.0 | -2.69 | $8.2.10^{-4}$ | 0.062039 | - 9.03314 | 0.0 | $-0.966.10^{-11}$ -0.0964 -0.2121 |
| | 8 | 0.0 | -6.69 | $8.2.10^{-4}$ | 0.104763 | -16.803712 | 0.0 | |
| | *9 | 0.1 | -1.69 | $8.2.10^{-4}$ | 0.0463 | - 7.358 | -0.19187577 | -0.004368 -0.08 -0.2008 |
| | 10 | 0.1 | -3.69 | $8.2.10^{-4}$ | 0.0732327 | -11.852796 | -0.1517993 | -0.0024 -0.105 -0.2236 |
| | 11 | 0.1 | -1.50 | $8.2.10^{-4}$ | 0.04295446 | - 7.1344151 | -0.254259 | -0.006 |
| | 12 | 1.0 | -1.0 | $8.2.10^{-4}$ | 0.0336 | - 9.1845 | -0.999 | -0.027 |
| | -13 | 0.05 | -1.69 | $8.2.10^{-4}$ | 0.04648 | - 7.139 | -0.142356 | -0.003 |

Table 6. Simulation Results - Lead/Lag Nonlinearities - Beaufort 8 Sea State

| ENCOUNTER ANGLE (DEG) $\beta$ | SWAY RATE $v$ (FT/SEC) | YAW RATE $r$ (DEG/SEC) | ROLL RATE $p$ (DEG/SEC) | ROLL $\phi$ (DEG) | YAW $\psi$ (DEG) | RUDDER ANGLE $\delta$ (DEG) | RUDDER RATE $\dot{\delta}$ (DEG/SEC) | MEAN YAW/SWAY RESISTANCE $a\ vr$ (lb) | MEAN RUDDER RESISTANCE $\delta^2$ (lb) | MEAN SWAY$^2$ RESISTANCE $\eta_v{}^2$ (lb) | MEAN TOTAL RESISTANCE $\overline{\Delta x}$ (lb) | $\lambda\ x^2$ (lb) | MEAN APPROX ADDED RESISTANCE $\bar{J}$ (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 Knots | | | | | | | | | | | | | |
| 30 | 0.773 | 0.159 | 0.148 | 1.541 | 5.106 | 0.993 | 0.134 | - 6540.6 | -339.[illegible] | | [illegible] | [illegible] | [illegible] |
| 60 | 0.930 | 0.223 | 1.495 | 5.357 | 3.739 | 0.468 | 0.092 | - 5844.7 | - 75.4 | | [illegible] | [illegible] | [illegible] |
| 90 | 2.365 | 0.072 | 1.748 | 2.999 | 0.303 | 0.113 | 0.064 | 11030.9 | - 4.6 | | [illegible] | [illegible] | [illegible] |
| 120 | 0.660 | 0.312 | 0.275 | 0.317 | 0.631 | 0.066 | 0.031 | 9131.7 | - 1.6 | | [illegible] | [illegible] | [illegible] |
| 23 Knots | | | | | | | | | | | | | |
| 30 | 0.520 | 0.150 | 0.411 | 1.724 | 2.275 | 0.546 | 0.095 | - 2276.1 | - 53.0 | | [illegible] | [illegible] | [illegible] |
| 60 | 1.148 | 0.324 | 6.100 | 17.369 | 2.269 | 0.226 | 0.056 | 3961.5 | - 9.6 | | [illegible] | [illegible] | [illegible] |
| 90 | 2.390 | 0.069 | 1.661 | 4.620 | 0.317 | 0.154 | 0.090 | 13224.7 | - 4.3 | | [illegible] | [illegible] | [illegible] |
| 120 | 0.662 | 0.262 | 0.267 | 0.366 | 1.242 | 0.120 | 0.031 | 8880.6 | - 2.7 | | [illegible] | [illegible] | [illegible] |
| 16 Knots | | | | | | | | | | | | | |
| 30 | 0.357 | 0.123 | 7.554 | 22.059 | 0.675 | 0.579 | 0.197 | 1105.6 | - 30.0 | | [illegible] | [illegible] | [illegible] |
| 60 | 0.888 | 0.310 | 3.263 | 9.043 | 1.666 | 0.273 | 0.089 | - 4629.9 | - 6.6 | | [illegible] | [illegible] | [illegible] |
| 90 | 2.407 | 0.067 | 1.604 | 2.706 | 0.533 | 0.271 | 0.141 | 14467.8 | - 6.4 | | [illegible] | [illegible] | [illegible] |
| 120 | 0.683 | 0.260 | 0.311 | 0.422 | 0.950 | 0.143 | 0.059 | 6703.2 | - 1.8 | | [illegible] | [illegible] | [illegible] |
| | | | | | | | | | | [illegible] | [illegible] | [illegible] | |

COMPARATIVE PERFORMANCE EVALUATION

A comparative evaluation between the digital adaptive controller defined and the existing Sperry Universal Gyropilot (UGP) aboard the Sea-Land McLean is complicated by the fact that the latter is not adaptive in the same sense as the former.

No provision for automatic adaptivity to either speed, load, or seaway exists in the Universal Gyropilot. Some adjustment of controller parameters is possible, however, through an operator interface.

The basis for operator action at specified operational conditions includes specification by the operator, of the following:

- "Weather adjust" zone width
- Rudder multiplier
- Rate multiplier

A performance evaluation was carried out using the non-linear time-domain simulation for a set of parameters optimized, as far as possible, to a criterion of minimum propulsion losses, at a specified design condition. The optimization of Universal Gyropilot parameters was made in the frequency domain by the same techniques as that applied to candidate lead/lag controllers for the adaptive controller.

For such optimization, a specification of recommended operator actions, in terms of those described above was made. It should be understood, however, that so long as the operator has no means to judge steering performance other than by observation of the course recorder, there is little likelihood of adherence to operator settings which minimize propulsion losses due to steering. For this reason the comparative evaluation contained in Tables 6 through 11 must be viewed in broader terms than a specific comparison of rms value of ship state and of mean added resistance of the ship across the spectrum of sea state, sea direction, and ship speed. The adaptive controller developed in the present program attempted to find a basis for automatic adaptivity to those ship operating parameters of importance in the minimization of propulsion losses. As such, it represented a significant advance over a system requiring human operator action and attention to satisfy control objectives which must, of necessity, be "operator subjective," at a particular point on the operating envelope of the ship.

Table 6 and 7 show the performance at Beaufort 8, speeds 32, 23, and 16 knots for the adaptive controller and UGP respectively. For comparison, the performance resulting from the uncontrolled ship is given in Table 8.

It may be seen that there is little difference in performance between the two controllers as specified.

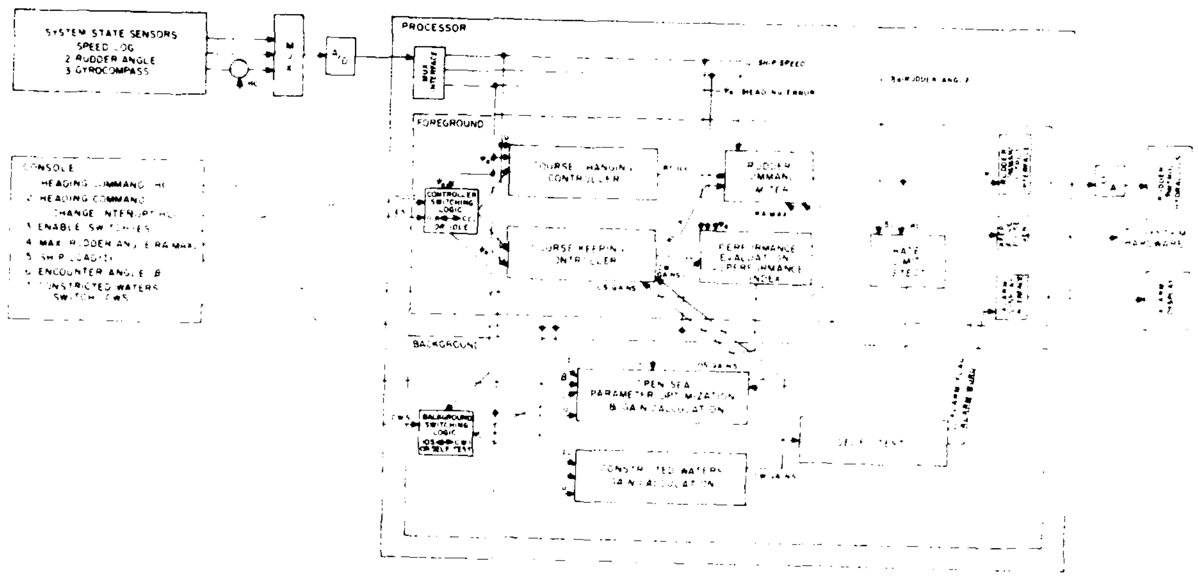


Figure 15. Block Diagram: Digital Adaptive Steering Control System

system, which automatically searches for an optimal operating point, has its origin in one of the first examples of adaptive control, reported by Draper and Li (Reference 20) in 1951.

The performance index selected for on-line minimization is that based on an approximation to added resistance due to steering, ie.,

$$J = \lambda \overline{\psi^2} + \overline{\delta^2} \tag{27}$$

where

$\overline{\psi^2}$ = variance of heading error

$\overline{\delta^2}$ = variance of rudder angle

with the constraint that rudder rate not saturate, i.e.,

$$\dot{\delta} < 2.3 \text{ deg/sec} \tag{28}$$

and $\lambda$, for a given load condition is of the form $\lambda = k_a/U^2$ ($k_a$ a constant) where $U$ is ship's speed through the water.

On-line minimization is achieved by means of a two-dimensional search, in the variables speed and encounter angle, for these control system parameters which minimized the performance index.

The controller whose parameters are continuously varied to achieve such criteria described above is a lead/lag plus integral controller of the form

$$\frac{\delta_c}{\psi_E} = \frac{K_1(1+T_1 s)}{(1+T_2 s)} + \frac{1}{T_I s} \tag{29}$$

The control system, in addition to open-sea course keeping to a criterion of minimum losses, has course-changing and confined-waters course keeping modes of operation.

The criterion for the course-changing mode is, basically, one of minimum speed loss in turning consistent with minimum overshoot; however, higher rates of turn might also be selected by the operator if required.

The criterion for confined-waters course keeping, where safety considerations override consideration of fuel economy, is one of minimum cross-track error.

A block diagram of the digital adaptive steering control system is shown in Figure 15.

This discussion of adaptivity in relation to sea conditions is based on a simplified approach to the problem based on control system bandwidth only. It is, however, reasonably applicable to the design of controllers based on minimization of the performance criterion Equation 23 and by proper design of the controller/ship's natural frequency (i.e., bandwidth); losses due to seaway disturbance may be significantly reduced. No assumptions regarding the phase relationship between yaw rate and sway resulting from seaway disturbance were necessary, or were made, as had been done by past workers (References 3, 8, 9, 12, 13). Instead the resulting losses were simply evaluated, as shown in Figure 4 by means of time-domain simulation.

Simulation results have shown that though a low bandwidth controller minimizes propulsion losses in quartering seas, reduction of yaw/sway losses of the hull can be achieved in following seas by the higher rudder activity caused by use of greater derivative control and a higher bandwidth controller. The limit to which the bandwidth can be raised is set by the magnitude of the resulting increased rudder losses.

It is true, almost without exception, that all past workers have stated the futility of heavy rudder activity in following seas, whether from a controllability or an economy standpoint (References 3, 5, 8, 12, 13). But few have specified the means by which this may be achieved, on a self-adaptive basis or otherwise.

The results of this study of the problem, as it relates to the SL-7, showed two main facts:

1) No potential for self-oscillations of the ship resulting from steering system nonlinearities existed, i.e., no limit cycles were present in calm water;

2) Propulsion losses then arose only as a result of seaway disturbance. These might be minimized by use, in general, of as low bandwidth a controller as is practicable, excepting the following sea case.

It was seen therefore that adaptivity of controller parameters to changing seaway encounter analysis led to a reduction of propulsion losses for high speeds and heavy quartering/following seas. A higher bandwidth controller (0.25 rad/sec) in these situations affected a reduction in net added resistance due to steering. The need for adaptivity to seaway encounter angles was therefore established if the ultimate in performance, in terms both of controllability and propulsion loses, was to be achieved.

To effect automatic adaptivity to seaway direction, the search method of self optimization to a criterion representative of added resistance may be extended from one dimension (speed) to the two-dimensions, speed and encounter angle.

## DEFINITION OF DIGITAL STEERING CONTROLLER

The controller chosen for minimization of propulsion losses due to steering in the open seas may be classified as a self-optimizing (Reference 19) type of adaptive control system. This type of control

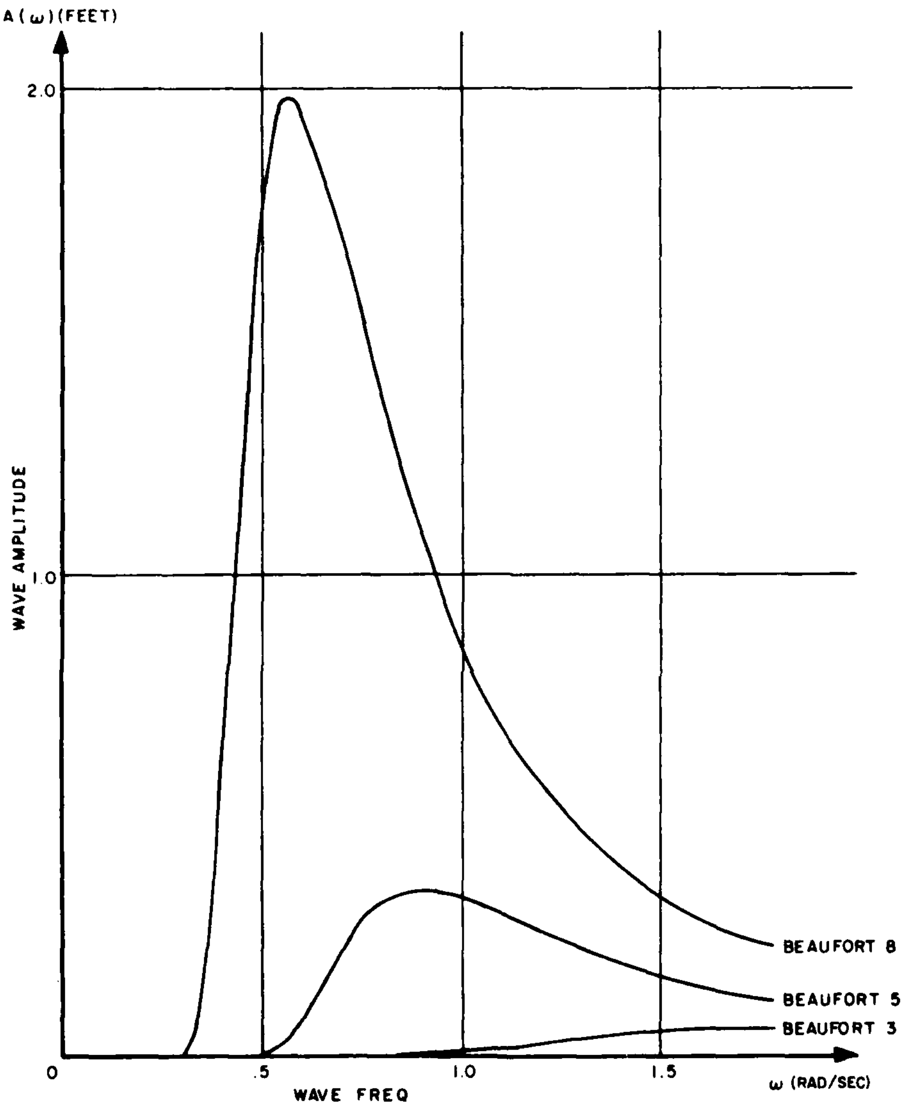


Figure 14. Wave Amplitude Versus Frequency for Various Beaufort Numbers (ISSC Spectrum)

Table 5. Encounter Frequency, $\omega_e$ Versus U Speed and Angle $\beta$

$$\omega_e = \frac{\omega^2}{g}\left(\frac{g}{\omega} - U\cos\beta\right)$$

$$\omega = 1.625 \text{ rad/sec}$$

| Encounter Angle (degree) $\beta$ | Speed (knots) U | | | | |
|---|---|---|---|---|---|
| | 10 | 15 | 19 | 24 | 30 |
| 0 | 0.2389 | -0.4542 | -1.0086 | -1.7017 | -2.5334 |
| 15 | 0.2861 | -0.3833 | -0.9189 | -1.5883 | -2.3917 |
| 30 | 0.4246 | -0.1756 | -0.6558 | -1.2560 | -1.9763 |
| 45 | 0.6449 | 0.1548 | -0.2373 | -0.7273 | -1.3154 |
| 60 | 0.931 | 0.5854 | 0.3082 | -0.0384 | -0.4542 |
| 75 | 1.266 | 1.0869 | 0.9434 | 0.7640 | 0.5487 |
| 90 | 1.6250 | 1.6250 | 1.6250 | 1.6250 | 1.6250 |
| 105 | 1.9838 | 2.1631 | 2.3066 | 2.4860 | 2.7013 |
| 120 | 2.3181 | 2.6646 | 2.9418 | 3.2884 | 3.7042 |
| 135 | 2.6051 | 3.0952 | 3.4873 | 3.9773 | 4.5654 |
| 150 | 2.8254 | 3.4256 | 3.9058 | 4.5060 | 5.2263 |
| 165 | 2.9639 | 3.6333 | 4.1689 | 4.8383 | 5.6417 |
| 180 | 3.0111 | 3.7042 | 4.2586 | 4.9517 | 5.7834 |

Table 4. Encounter Frequency Versus Speed and Angle

$$\omega_e = \frac{\omega^2}{g}\left(\frac{g}{\omega} - U\cos\beta\right)$$

$$\omega = .325 \text{ rad/sec}$$

| Encounter Angle (degree) $\beta$ | Speed (knots) $U$ | | | | | |
|---|---|---|---|---|---|---|
| | 10 | 15 | 19 | 24 | 30 | 32 |
| 0 | 0.2696 | 0.2418 | 0.2197 | 0.1919 | 0.1587 | 0.1476 |
| 15 | 0.2714 | 0.2447 | 0.2232 | 0.1965 | 0.1643 | 0.1536 |
| 30 | 0.2770 | 0.2530 | 0.2338 | 0.2098 | 0.1809 | 0.1713 |
| 45 | 0.2858 | 0.2662 | 0.2505 | 0.2309 | 0.2074 | 0.1995 |
| 60 | 0.2973 | 0.2834 | 0.2723 | 0.2585 | 0.2418 | 0.2363 |
| 75 | 0.3106 | 0.3035 | 0.2977 | 0.2906 | 0.2819 | 0.2791 |
| 90 | 0.3250 | 0.3250 | 0.3250 | 0.3250 | 0.3250 | 0.3250 |

Table 3. Encounter Frequency, $\omega_e$ Versus U Speed and Angle $\beta$

$$\omega_e = \frac{2\pi}{\lambda}\left(\sqrt{\frac{g\lambda}{2\pi}} - U\cos\beta\right)$$

$\lambda = 518$ ft  $\omega = .625$ rad/sec

| Encounter Angle (degree) | Speed (knots) U | | | | |
|---|---|---|---|---|---|
| | 10 | 15 | 19 | 24 | 30 |
| $\beta$ 0 | 0.4199 | 0.3174 | 0.2355 | 0.1331 | 0.0101 |
| 15 | 0.4268 | 0.3279 | 0.2487 | 0.1498 | 0.0311 |
| 30 | 0.4473 | 0.3586 | 0.2876 | 0.1989 | 0.0925 |
| 45 | 0.4799 | 0.4074 | 0.3495 | 0.2771 | 0.1901 |
| 60 | 0.5223 | 0.4711 | 0.4301 | 0.3789 | 0.3174 |
| 75 | 0.5717 | 0.5452 | 0.5240 | 0.4975 | 0.4656 |
| 90 | 0.6247 | 0.6247 | 0.6247 | 0.6247 | 0.6247 |
| 105 | 0.6777 | 0.7042 | 0.7254 | 0.7520 | 0.7838 |
| 120 | 0.7271 | 0.7784 | 0.8193 | 0.8705 | 0.9320 |
| 135 | 0.7696 | 0.8420 | 0.8999 | 0.9724 | 1.0593 |
| 150 | 0.8021 | 0.8908 | 0.9618 | 1.0505 | 1.1569 |
| 165 | 0.8226 | 0.9215 | 1.0007 | 1.0996 | 1.2183 |
| 180 | 0.8296 | 0.9320 | 1.0139 | 1.1164 | 1.2393 |

where

$\lambda$ = wavelengths

$C_w$ = wave celerity

$U$ = ship's speed

$\beta$ = encounter angle

Alternatively, it may be written as

$$\omega_e = \frac{\omega^2}{g}\left(\frac{g}{\omega} - U\cos\beta\right) \tag{26}$$

where $\omega$ is the wave circular frequency. Discussion of encounter frequency as described by Equations 25 and 26 may be made in conjunction with, first Tables 3 through 5, which show the relation of $\omega_e$ to $U$ and $\beta$ for the wave frequency component of a Beaufort 8 seaway (which carries the highest energy components, i.e., $\omega$ = 0.625 rad/sec) and Table 3, for the lowest frequency($\omega$= 0.325 rad/sec), and the effective highest frequency ( $\omega$ = 1.625 rad/sec), respectively. For a given speed, the encounter frequency reduces with encounter angle for a given particular wavelength; for a given encounter angle the encounter angle reduces with speed. To attempt to block the effect of the seaway disturbances from the control system at Beaufort 8, say, at any given encounter angle, for a given speed, it was first thought that the control system bandwidth should be less than:

a) The encounter frequency resulting from the highest energy bearing wave frequency of 0.625 rad/sec for Beaufort 8;

b) The encounter wave frequency resulting from the lowest frequency of 0.325 rad/sec for Beaufort 8; and

c) The encounter frequency resulting from the effective highest wave frequency of 1.625 rad/sec for Beaufort 8.

In general, it would not be possible to achieve item "c" in following through quartering seas, since, as can be seen from Table 5, the encounter frequencies in these cases are negative. This represents simply a folding over of the encounter frequency spectrum. However, in crossing over, the encounter frequencies must approach and pass through zero encounter frequency, so that nothing other than a "zero bandwidth" controller could block all components.

And from the spectra shown in Figure 14 for Beaufort No. 8, 5, and 3, it is clear that not only does a significant reduction in wave amplitudes occur with decreasing sea state, but also that the component waves are of higher frequency. Satisfaction of "a" above for Beaufort 8 therefore results in satisfaction for all lower sea states.

Speed Adaptivity

Adaptivity of the controller parameters to speed could be achieved on-line by interpolation of the above a priori computed parameters set for appropriate speeds, as a function of speed only - a one-dimensional search.

No on-line minimization of the performance index would be necessary, in theory, since it is known, a priori, that these controller parameters, at these speeds, minimize added resistance due to steering. However, no means would then be available to the system to compensate itself for the inevitable errors in the ship parameters modeling.

If, on the other hand, the performance criterion employed in on-line minimization were truly representative, at all speeds, of added resistance due to steering, then the system might be permitted to search automatically in one dimension (speed) for those sets of parameters which do minimize the performance index on-line.

Load Adaptivity

The parameters evaluated relate to a fully loaded vessel. For different loading conditions, other sets of parameter combinations would be appropriate. These values would be calculated a priori in the same manner as those for the fully loaded ships. Selection of parameters sets for a particular loading condition would seem best achieved by manual entry of load conditions.

Normal operation of the SL-7 is at, or near, full-load condition. The need for load adaptivity on this particular vessel is, therefore, debatable.

For most ships of the tanker or bulk carrier types, full-load and ballast are the load conditions of interest.

In the general case, full-load, part-load, and ballast conditions could be provided for by means of manual selection control.

Sea Condition Adaptivity

The need for adaptivity of the control system parameters to seaway direction at a given sea state and sea state to minimize the performance criterion (Equation 23) may be discussed in relation to adaptivity to speed. Given that greater or lesser wave amplitudes result in greater or lesser disturbances on the ship, the environmental parameter of importance in terms of minimization of a particular steering criterion is ship/seaway encounter frequency $\omega_e$. This is given by

$$\omega_e \triangleq \frac{2\pi}{\lambda}\left(c_w - V\cos\beta\right) \tag{25}$$

$\psi$ = heading deviation

$\delta$ = rudder angle

$X'_{vr}$ = nonlinear force coefficient due to yaw/sway

$X'_{\delta\delta}$ = nonlinear force coefficient due to rudder angle

$U$ = ship's speed

$\omega$ = the natural frequency of closed-loop oscillation of ship/steering system

The use of such a criterion could be expected to minimize resistance due to yaw/sway of the ship and to rudder angle resulting from oscillations at the natural frequency of the ship/steering system closed loop. In addition, by suitable choice of the natural frequency, the resistance losses caused by external seaway disturbance forced oscillations may be minimized

The form of $\mathcal{J}$ followed that of added resistance as a function of encounter angle, with maximum and minimum values occurring at similar seaway directions (See Figure 4). Minimization of one would appear to result in minimization of the other for the candidate controller configured.

To the extent that resistance is minimized, yaw deviations will be constrained through the use of such a criterion.

Previous workers (References 3, 5, 8, 10 13) have predicted by regular wave analysis, or simply assumed, that the phase relationship between yaw rate and sway velocity, resulting from seaway disturbance in predominantly following seas, was such that little or no penalty in drag was paid by yaw/sway of the ship. Further, the criterion of Equation 23 was derived based on the assumption of an in-phase relationship of yaw rate to sway. Clearly, in both cases, the actual phase relationship of sway velocity to yaw rate is critical to propulsion losses. And certainly it seemed reasonable to assume that control system bandwidth was not the only factor which could effect a change in this relationship. Minimization of a criterion based on actual added resistance, that of the performance criterion of Equations 4 and 5 required no assumption regarding the form and type of motion. Instead, the object simply became that of minimizing the performance index in all situations. An extension of modern linear control theory was well suited to the system of candidate controllers to minimize the latter criterion. However, through perfomance evaluation of candidate controllers based on the linear quadratic Gaussian (LQG) design method, over a wide range of weightings of various performance indexes failed, in general, to yield candidate controllers which could compare, in terms of minimum propulsion losses, with those controllers synthesized by parameter optimization techniques.

CONTROL SYSTEM ADAPTIVITY

Adaptivity of control system parameters resulting from minimization of Equation 23 to speed, sea conditions, and load may be considered as follows:

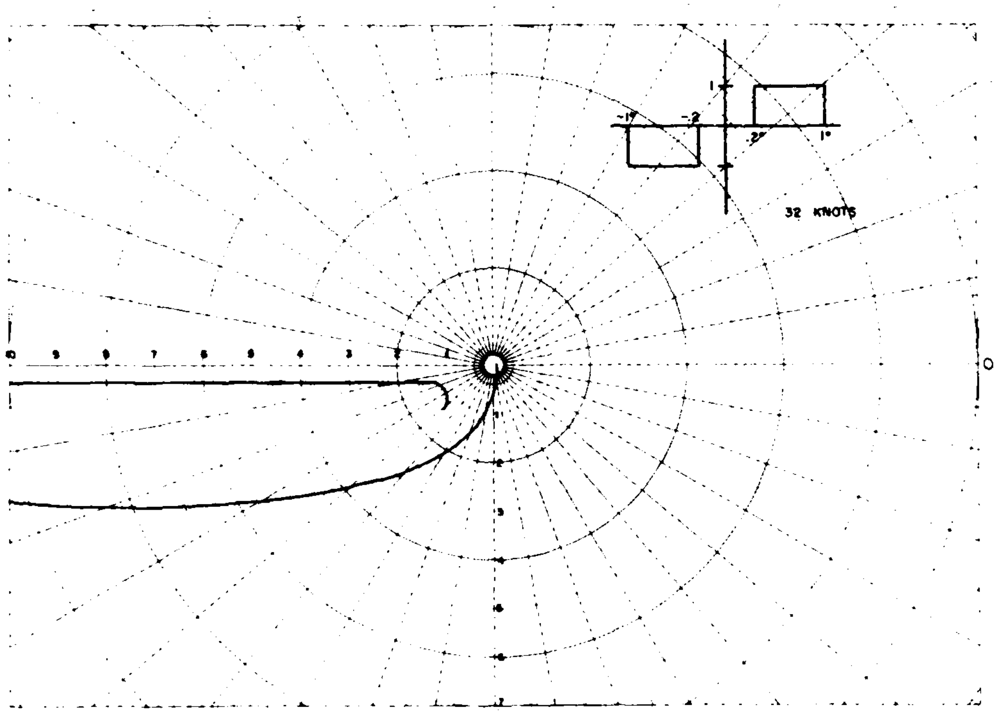


Figure 13. Steering System with RPU Hysteresis and Deadband Nonlinearity: Amplitude and Frequency Loci

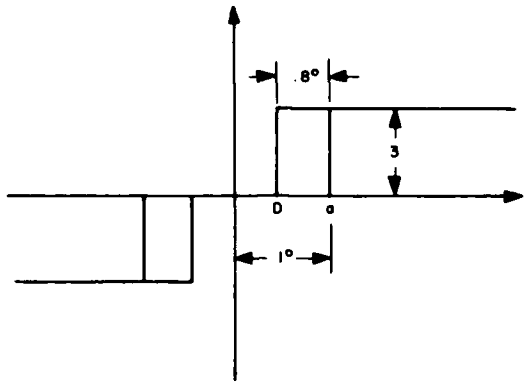


Figure 12. RPU Nonlinearity and Describing Function

As may be seen from Figure 13, the requirement for Equation 21 to be met, intersection of the curves

$$\phi_1(\omega)\,\phi_2(\omega) + K/j\omega \qquad (22)$$

and

$$-1/N(x)$$

for the given RPU and optimal lead/lag controller at 32 knots, does not occur. No potential for limit-cycle oscillations in calm water due to steering gear nonlinearities therefore exists.

CONTROL SYSTEM TRADEOFFS

Candidate control system parameters have been defined for speeds of 32, 23, and 16 knots.

One criterion to which candidate controllers were designed was of the form

$$J = \lambda\,\overline{\psi^2} + \overline{\delta^2} \qquad (23)$$

where, for a given load

$$\lambda = f(X'_{vr}, X'_{\delta\delta}, U, \omega) \qquad (24)$$

Table 7. Simulation Results - UGP No. 4 - Controller Parameters $\begin{bmatrix} 1/3 \\ 53.0 \\ 3.0 \end{bmatrix}$ - Beaufort 8 Sea State

| ENCOUNTER ANGLE (DEG) $\beta$ | SWAY RATE $v$ (FT/SEC) | YAW RATE $r$ (DEG/SEC) | ROLL RATE $p$ (DEG/SEC) | ROLL $\phi$ (DEG) | YAW $\psi$ (DEG) | RUDDER ANGLE $\delta$ (DEG) | RUDDER RATE $\dot{\delta}$ (DEG/SEC) | MEAN YAW/SWAY RESISTANCE $a\ vr$ (lb) | MEAN RUDDER RESISTANCE $\delta^2$ (lb) | MEAN SWAY2 RESISTANCE $\eta v^2$ (lb) | MEAN TOTAL RESISTANCE $\underline{\Delta x}$ (lb) | $\lambda\ x^2$ (lb) | MEAN APPROX ADDED RESISTANCE $\overline{J}$ (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 Knots | | | | | | | | | | | | | |
| 30 | 0.812 | 0.162 | 0.137 | 1.602 | 5.557 | 0.839 | 0.076 | - 7498.0 | -242.9 | | -8351.2 | -45061.1 | -45924.0 |
| 60 | 0.914 | 0.227 | 1.517 | 5.419 | 3.139 | 0.714 | 0.177 | - 5816.1 | -175.1 | | -6762.6 | -14184.6 | -14359.9 |
| 90 | 2.364 | 0.072 | 1.753 | 3.014 | 0.321 | 0.094 | 0.034 | 11022.1 | - 3.0 | | 5649.8 | - 176.5 | - 179.6 |
| 120 | 0.677 | 0.312 | 0.277 | 0.316 | 0.547 | 0.195 | 0.138 | 9202.3 | - 13.3 | | 6764.3 | - 639.9 | - 653.3 |
| 23 Knots | | | | | | | | | | | | | |
| 30 | 0.523 | 0.153 | 0.411 | 1.722 | 2.452 | 0.584 | 0.116 | - 2382.0 | - 60.4 | | -2694.4 | - 8505.7 | - 8566.1 |
| 60 | 1.142 | 0.329 | 5.907 | 16.830 | 1.640 | 0.713 | 0.264 | 4022.8 | - 90.6 | | 2727.5 | - 4310.8 | - 4401.4 |
| 90 | 2.390 | 0.069 | 1.669 | 2.846 | 0.305 | 0.078 | 0.027 | 13146.4 | - 1.2 | | 7862.9 | - 311.0 | - 312.2 |
| 120 | 0.657 | 0.263 | 0.288 | 0.363 | 0.888 | 0.228 | 0.147 | 8986.3 | - 9.4 | | 8576.2 | - 1246.1 | - 1255.5 |
| 16 Knots | | | | | | | | | | | | | |
| 30 | 0.362 | 0.127 | 7.915 | 23.125 | 0.863 | 0.684 | 0.231 | 1147.5 | - 41.2 | | 965.3 | - 3431.6 | - 3472.9 |
| 60 | 0.890 | 0.314 | 3.062 | 8.446 | 1.636 | 0.580 | 0.243 | - 4965.0 | - 29.0 | | -5725.8 | - 4067.9 | - 4096.9 |
| 90 | 2.406 | 0.067 | 1.618 | 2.752 | 0.437 | 0.094 | 0.037 | 14389.0 | - 0.9 | | 9031.4 | - 400.2 | - 401.1 |
| 120 | 0.679 | 0.261 | 0.315 | 0.439 | 0.826 | 0.264 | 0.159 | 8793.4 | - 6.0 | | 8361.3 | - 1140.9 | - 1146.9 |
| | | | | | | | | | | UGP No. 4 Nonlinear | | | |

Table 8. Simulation Results - Open-Loop - Controller Parameter - Beaufort 8 Sea States

| ENCOUNTER ANGLE (DEG) $\beta$ | SWAY RATE $\dot{v}$ (FT/SEC) | YAW RATE $r$ (DEG/SEC) | ROLL RATE $p$ (DEG/SEC) | ROLL $\phi$ (DEG) | YAW* $\psi$ (DEG) | RUDDER ANGLE $\delta$ (DEG) | RUDDER RATE $\dot{\delta}$ (DEG/SEC) | MEAN YAW/SWAY RESISTANCE [illegible] | MEAN RUDDER RESISTANCE $\delta^2$ [illegible] | MEAN SWAY2 RESISTANCE $\eta_v{}^2$ [illegible] | MEAN TOTAL RESISTANCE $\overline{\Delta X}$ [illegible] | $\lambda$ $x^2$ [illegible] | MEAN APPROX ADDED RESISTANCE $\overline{J}$ [illegible] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible] | | | | | | | | | | | | | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | [illegible] | - | | [illegible] | - | - |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | [illegible] | | | [illegible] | | - |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | [illegible] | - | | [illegible] | | - |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | [illegible] | - | | [illegible] | - | - |
| [illegible] | | | | | | | | | | | | | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | [illegible] | - | | [illegible] | - | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | [illegible] | | | [illegible] | - | - |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | [illegible] | - | | [illegible] | | - |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | | - | [illegible] | - | | [illegible] | - | |
| [illegible] | | | | | | | | | | | | | |
| | [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | [illegible] | - | | [illegible] | - | - |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | [illegible] | - | | [illegible] | | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | [illegible] | - | | [illegible] | | - |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | - | - | [illegible] | | | [illegible] | - | - |
| | | | | | *Mean Variance | | | | | [illegible] | [illegible] | [illegible] | |

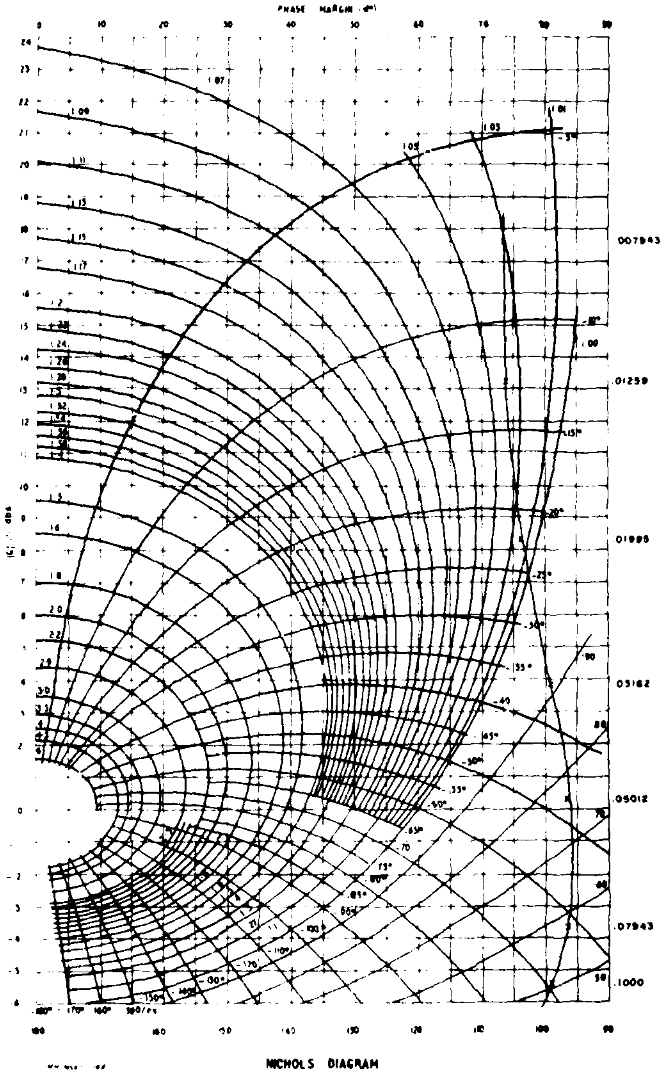


Figure 16. UGP No. 4 - 32 Knots (1/3, 53, 3)

Table 9. Simulation Results - UGP No. 1 - Controller Parameters $\begin{bmatrix} 1/3 \\ 103 \\ 3 \end{bmatrix}$ - Beaufort 8 Sea State

| ENCOUNTER ANGLE (DEG) $\beta$ | SWAY RATE $v$ (FT/SEC) | YAW RATE $r$ (DEG/SEC) | ROLL RATE $p$ (DEG/SEC) | ROLL $\phi$ (DEG) | YAW $\psi$ (DEG) | RUDDER ANGLE $\delta$ (DEG) | RUDDER RATE $\dot{\delta}$ (DEG/SEC) | MEAN YAW/SWAY RESISTANCE $a\ vr$ (lb) | MEAN RUDDER RESISTANCE $\delta^2$ (lb) | MEAN SWAY$^2$ RESISTANCE $\eta_v v^2$ (lb) | MEAN TOTAL RESISTANCE $\overline{\Delta X}$ (lb) | $\lambda\ \epsilon^2$ (lb) | MEAN APPROX ADDED RESISTANCE $\bar{J}$ (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 Knots | | | | | | | | | | | | | |
| 30 | 0.734 | 0.157 | 0.167 | 1.537 | 4.187 | 1.328 | 0.156 | - 5731.7 | -605.5 | | -6635.4 | -26737.6 | -27343.1 |
| 60 | 0.901 | 0.234 | 1.564 | 5.564 | 2.341 | 1.340 | 0.356 | - 6184.3 | -615.9 | | -7550.0 | - 6159.6 | - 6775.6 |
| 90 | 2.365 | 0.072 | 1.748 | 2.997 | 0.315 | 0.130 | 0.057 | 11049.7 | - 6.1 | | 5673.1 | - 179.6 | - 165.7 |
| 120 | 0.677 | 0.312 | 0.278 | 0.326 | 0.557 | 0.332 | 0.224 | 9263.0 | - 38.0 | | 8801.4 | - [illegible] | - 763.1 |
| 23 Knots | | | | | | | | | | | | | |
| 30 | 0.490 | 0.158 | 0.414 | 1.732 | 1.747 | 1.105 | 0.243 | - 2106.8 | -215.6 | | -2544.4 | - 4466.2 | - 4662.0 |
| 60 | 1.149 | 0.333 | 5.912 | 16.806 | 1.364 | 1.114 | 0.414 | 3617.6 | -220.1 | | 2379.2 | - 3153.0 | - 3373.1 |
| 90 | 2.390 | 0.069 | 1.663 | 2.827 | 0.281 | 0.134 | 0.059 | 13223.0 | - 3.3 | | +7939.0 | - 112.7 | - 116.0 |
| 120 | 0.655 | 0.263 | 0.291 | 0.387 | 0.707 | 0.385 | 0.243 | 9072.7 | - 26.5 | | 6648.0 | - 666.5 | - 693.0 |
| 16 Knots | | | | | | | | | | | | | |
| 30 | 0.350 | 0.127 | 7.245 | 21.175 | 0.947 | 1.150 | 0.384 | 623.4 | -114.5 | | 395.5 | - 4530.6 | - 4645.3 |
| 60 | 0.893 | 0.314 | 3.029 | 8.334 | 1.292 | 0.873 | 0.359 | - 5090.0 | - 65.6 | | -5892.5 | - 2499.6 | - 2565.4 |
| 90 | 2.405 | 0.067 | 1.610 | 2.726 | 0.465 | 0.148 | 0.065 | 14545.3 | - 2.0 | | +9192.5 | - 332.3 | - 334.3 |
| 120 | 0.677 | 0.261 | 0.317 | 0.463 | 0.671 | 0.452 | 0.264 | 8877.2 | - 17.6 | | 8435.7 | - 676.3 | - 693.9 |
| | | | | | | | | | | UGP No. 1 Nonlinear | Solution | | |

Table 10. Simulation Results - UGP NO. 2 - Controller Parameters $\begin{bmatrix} 1.0 \\ 103.0 \\ 3.0 \end{bmatrix}$ - Beaufort 8 Sea State

| ENCOUNTER ANGLE (DEG) $\beta$ | SWAY RATE $v$ (FT/SEC) | YAW RATE $r$ (DEG/SEC) | ROLL RATE $p$ (DEG/SEC) | ROLL $\phi$ (DEG) | YAW $\psi$ (DEG) | RUDDER ANGLE $\delta$ (DEG) | RUDDER RATE $\dot{\delta}$ (DEG/SEC) | MEAN YAW/SWAY RESISTANCE $a\ vr$ (lb) | MEAN RUDDER RESISTANCE $\delta^2$ (lb) | MEAN SWAY$^2$ RESISTANCE $\eta_v{}^2$ (lb) | MEAN TOTAL RESISTANCE $\overline{\Delta X}$ (lb) | $\lambda\ x^2$ (lb) | MEAN APPROX ADDED RESISTANCE $\overline{J}$ (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 Knots | | | | | | | | | | | | | |
| 30 | 0.652 | 0.164 | 0.569 | 4.201 | 2.059 | 4.091 | 0.477 | - 6935.6 | -5725.2 | | -13053.8? | [illegible] | [illegible] |
| 60 | 0.973 | 0.278 | 2.524 | 9.563 | 1.715 | 2.465 | 0.558? | - 3173.9 | -2086.3 | | - 6134.6? | -4161.? | [illegible] |
| 90 | 2.369 | 0.079 | 0.90 | 1.546 | 0.246 | 0.321 | 0.120 | 11634.8 | - 35.5 | | 6410.7? | - 59.1? | [illegible] |
| 120 | 0.664 | 0.312 | 0.247 | 0.868 | 0.608 | 0.746 | 0.291 | 9180.4 | - 192.2? | | 6574.? | [illegible] | [illegible] |
| 23 Knots | | | | | | | | | | | | | |
| 30 | 0.611 | 0.152 | 2.452 | 10.576 | 1.253 | 2.313 | 0.467 | - 2425.5 | - 945.3 | | - 3714.9? | [illegible] | [illegible] |
| 60 | 1.040 | 0.309 | 1.199 | 3.628 | 0.995 | 1.426 | 0.482 | - 4332.4 | - 361.9 | | - 5693.0? | -1410.? | [illegible] |
| 90 | 2.393 | 0.074 | 0.817 | 1.383 | 0.320 | 0.294 | 0.168 | 13638.0 | - 15.4 | | 8325.5? | - 144.1 | [illegible] |
| 120 | 0.663 | 0.262 | 0.235 | 0.782 | 0.501 | 0.721 | 0.300 | 9016.9 | - 92.4 | | 8516.7? | - 355.8? | [illegible] |
| 16 Knots | | | | | | | | | | | | | |
| 30 | 0.274 | 0.116 | 0.573 | 2.012 | 0.529 | 1.084 | 0.303 | - 995.5 | - 101.1 | | - 1166.6? | - 504.7? | [illegible] |
| 60 | 0.882 | 0.365 | 0.694 | 1.977 | 0.975 | 1.209 | 0.428 | - 6474.1 | - 126.1 | | - 7315.7? | [illegible] | - 140?.? |
| 90 | 2.409 | 0.071 | 0.765 | 1.280 | 0.333 | 0.296 | 0.098 | 14802.5 | - 7.6 | | 9430.5? | - 157.1? | [illegible] |
| 120 | 0.665 | 0.261 | 0.284 | 1.099 | 0.664 | 0.946 | 0.323 | 8757.5 | - 77.1 | | 8246.1? | - 622.? | [illegible] |

[illegible] 2 corrected Roll Nonlinear solution

The Nichols diagram for these UGP settings is shown in Figure 16 for a speed of 32 knots. It can be seen that the control setting results in an extremely stable system, with phase margin not less than 65 degrees, and a very large gain margin. The closed-loop bandwidth for this setting controller at 32 knots (i.e., at 3 db point) is around 0.06 rad/sec.

This, then, represents the optimal performance which can be obtained by very definite specified settings by the operator of the Universal Gyropilot. What is the result of the operator varying these settings from these specified values?

Table 10 shows the performance resulting from a Rudder Mult gain setting of 3, together with a Rate Mult setting of 2, still with the Weather Adjust zone set at 5. Comparison with Table 9 shows the following:

- At 32 knots, the major effect was a substantial increase in total added resistance at 30 degrees encounter angle. This resulted from the rudder angles resulting from this controller setting, which brought about more than a 50 percent reduction in rms heading error for this angle

- Heavier penalties in increased added resistance resulted in quartering/following seas at the lower speeds. Yaw deviation has been reduced in all cases

The inference is clear. The normal tendency of the operator is to alter the setting to bring about reduction in heading error. The result is an increased penalty in propulsion losses.

Consider now the case where the Weather Adjust zone is set to 0, the Rudder Mult gain is at 3, and the Rate Mult setting is 1. The resulting performance is shown in Table 11 and can be summarized as follows:

- Compared to the optimal settings case, very heavy penalties in total added resistance resulted for quartering and following seas at all speeds

- Heading error has been reduced significantly in quartering and following seas at high speed

If we turn, now, to a discussion of system stability for these UGP controller settings other than the "optimum," a more alarming picture is immediately obvious, using control settings of Rudder Mult: 3, Rate Mult: 2, and Weather Adjust: 5. The frequency characteristics are shown on the Nichols diagram of Figure 17, for a speed of 32 knots. It can be seen that at high speeds, this controller exhibited poor phase and gain margins of stability.

Figure 18, shows similar data for the control setting Rudder Mult: 3; Rate Mult: 1; and Weather Adjust: 0. Stability at high speed was extremely poor and can be considered marginal, at best.

TAble 11. Simulation Results - UGP No. 6 - Controller Parameters $\begin{bmatrix} 3.0 \\ 53.0 \\ 3.0 \end{bmatrix}$ - Beaufort 8 Sea State

| ENCOUNTER ANGLE (DEG) $\beta$ | SWAY RATE $v$ (FT/SEC) | YAW RATE $r$ (DEG/SEC) | ROLL RATE $p$ (DEG/SEC) | ROLL $\phi$ (DEG) | YAW $\psi$ (DEG) | RUDDER ANGLE $\delta$ (DEG) | RUDDER RATE $\dot{\delta}$ (DEG/SEC) | MEAN YAW/SWAY RESISTANCE $a\ vr$ (lb) | MEAN RUDDER RESISTANCE $\delta^2$ (lb) | MEAN SWAY$^2$ RESISTANCE $\eta_v{}^2$ (lb) | MEAN TOTAL RESISTANCE $\Delta x$ (lb) | $\lambda\ \epsilon^2$ (lb) | MEAN APPROX ADDED RESISTANCE $\bar{J}$ (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 Knots | | | | | | | | | | | | | |
| 30 | 1.215 | 0.297 | 0.783 | 7.409 | 3.939 | 6.469 | 0.634 | -31846.8 | -14312.7 | | -47522.0 | -22565.8 | -36878.5 |
| 60 | 1.204 | 0.314 | 2.531 | 10.572 | 2.349 | 4.921 | 0.606 | -14915.0 | - 8298.1 | | -24552.0 | - 7830.5 | -16128.6 |
| 90 | 2.370 | 0.080 | 0.906 | 1.653 | 0.169 | 0.502 | 0.148 | 11524.2 | - 87.4 | | 6240.7 | - 55.9 | - 143.4 |
| 120 | 0.703 | 0.314 | 0.295 | 1.545 | 0.618 | 1.421 | 0.323 | 8560.6 | - 691.6 | | 7411.8 | - 580.3 | - 1272.0 |
| 23 Knots | | | | | | | | | | | | | |
| 30 | 0.798 | 0.200 | 2.443 | 10.905 | 2.086 | 4.082 | 0.551 | - 8388.3 | - 2953.5 | | -11930.4 | - 6166.2 | - 9119.7 |
| 60 | 1.048 | 0.308 | 1.210 | 3.748 | 1.054 | 1.692 | 0.487 | - 4717.8 | - 511.1 | | - 6243.8 | - 1584.5 | - 2095.0 |
| 90 | 2.397 | 0.078 | 0.822 | 1.525 | 0.298 | 0.513 | 0.148 | 13382.0 | - 46.6 | | 6023.6 | - 131.9 | - 176.6 |
| 120 | 0.676 | 0.264 | 0.305 | 1.396 | 0.632 | 1.332 | 0.333 | 8510.3 | - 314.3 | | 7770.8 | - 594.5 | - 906.6 |
| 16 Knots | | | | | | | | | | | | | |
| 30 | 0.414 | 0.152 | 0.616 | 2.833 | 1.262 | 2.767 | 0.368 | - 4070.0 | - 656.3 | | - 4884.6 | - 2401.0 | - 3657.3 |
| 60 | 0.923 | 0.314 | 0.736 | 2.606 | 1.580 | 2.299 | 0.462 | - 8535.3 | - 454.5 | | - 9777.4 | - 3542.3 | - 3996.6 |
| 90 | 2.409 | 0.074 | 0.771 | 1.400 | 0.259 | 0.475 | 0.148 | 14707.6 | - 19.3 | | 9317.4 | - 109.1 | - 126.5 |
| 120 | 0.744 | 0.278 | 0.423 | 2.397 | 1.161 | 2.794 | 0.437 | 5962.1 | - 670.7 | | 4779.6 | - 1975.4 | - 2646.1 |
| | | | | | | | | | | UGP No. 6 Corrected Nonlinear | Roll Solution | | |

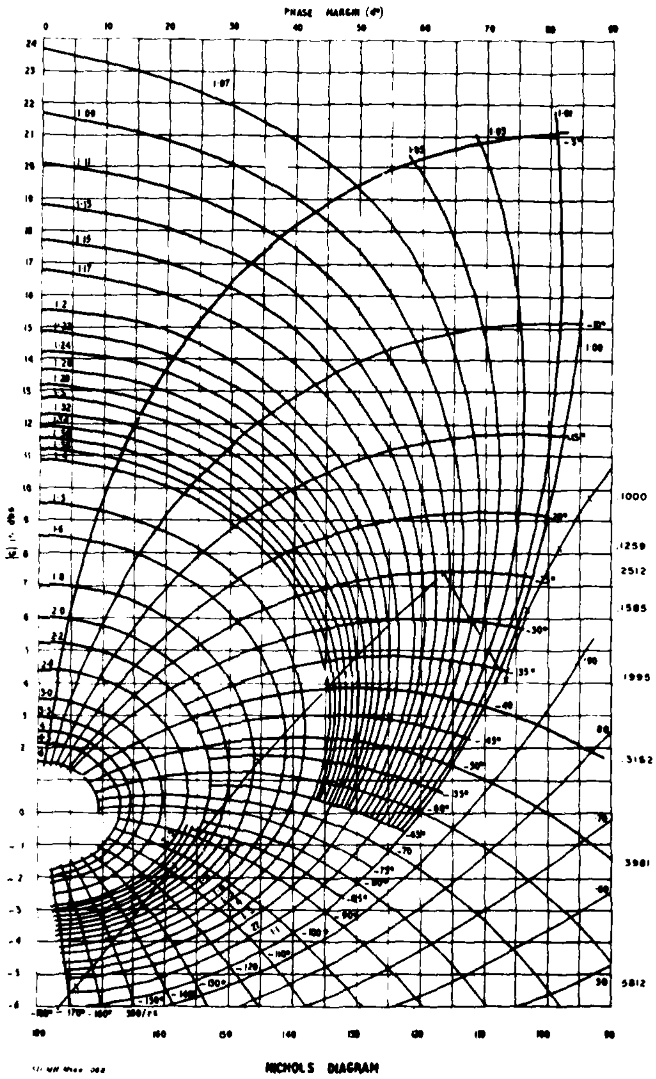


Figure 17.  UGP No. 2 - 32 Knots (1, 103, 3)

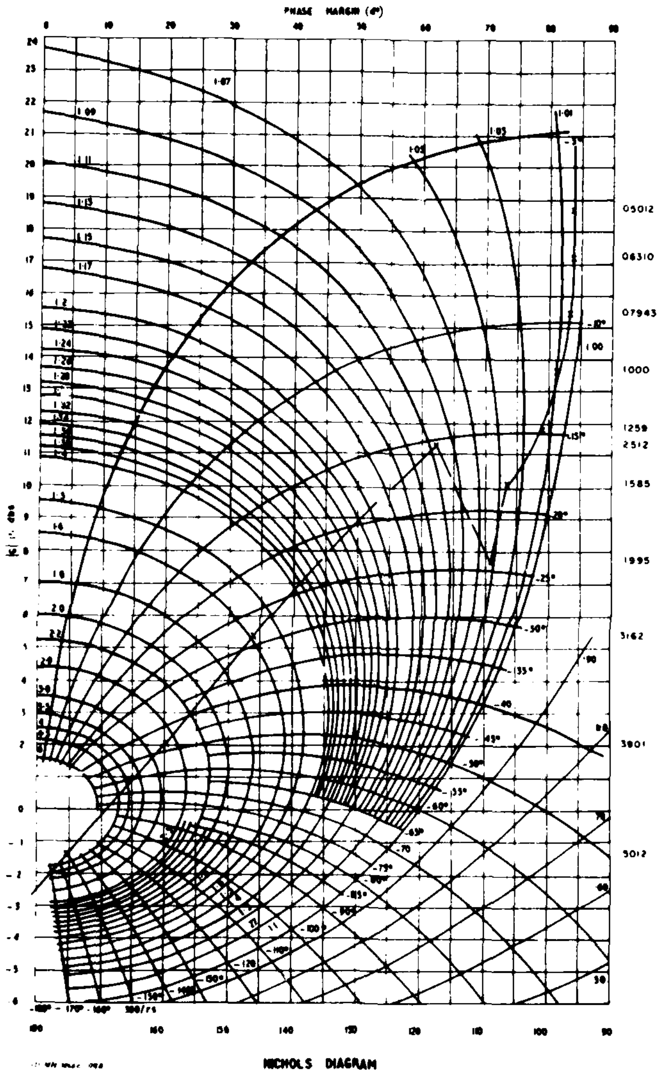


Figure 18. UGP No. 6 - 32 Knots (3, 53, 3)

It is on this overall basis that a comparison between the adaptive steering control system design, which has resulted from the work done on this program to date, and the Universal Gyropilot presently on the SL-7 should be made.

## EFFECTS OF STEERING GEAR NONLINEARITIES ON SYSTEM PERFORMANCE

The basic system optimization was carried out without consideration of the steering gear nonlinearities. Specifically, the effect of the Rotary Power Unit was neglected in the design technique.

Final system performance evaluation, however, included the effects of this nonlinearity, and, further, much analytical work was carried out in an investigation into possible limit cycles resulting from the Rotary Power Unit. It was determined that no potential for limit cycles of the ship existed in calm water for the controller specified.

To demonstrate the effect of the Rotary Power Unit nonlinearity on heavy weather performance, the following configurations were evaluated:

- The hydraulics modeled simply as the first-order lag resulting from the main pump - this corresponds to the assumption of no pump saturation
- The main pump nonlinearities modeled, but the Rotary Power Unit nonlinearities neglected - this corresponds to a single-loop steering system
- Inclusion of Rotary Power Unit deadband and hysteresis - this corresponds to a two-loop "bang-bang" system
- Replacement of Rotary Power Unit deadband and hysteresis with a proportional controller over the range of the existing system deadband - this is a hypothetical two-loop proportional system

A comparison of performance resulting from these various configurations for a design condition of 32-knots speed, Beaufort 8 gale condition, seaway direction 60 degrees off the stern is shown in Table 12. It can be seen that:

- The effect of the inclusion of the Rotary Power Unit causes a significant degradation in heading performance. This is caused by the reduced rudder angles and rudder activity resulting from such inclusion. For the particular seaway direction there results some reduction in total added resistance
- No improvement is brought about through the use of a proportional control of the Rotary Power Unit, using this particular value of proportional range, over the deadband/hysteresis system

Table 12. Simulation Results - Controller Parameters $\begin{bmatrix} 0.2188 \\ 44.92 \\ 7.066 \end{bmatrix}$
Beaufort 8 Sea State - 32 Knots
Effect of Rotary Power Unit -
No Gimbaling Error - Optimal Controller
= 60 Degrees; Discrete Controller
$T_{sample} = 1.0$, $T_{control} = 3.0$

| ENCOUNTER ANGLE (DEG) $\beta$ | SWAY RATE $v$ (FT/SEC) | YAW RATE $r$ (DEG/SEC) | ROLL RATE $p$ (DEG/SEC) | ROLL $\phi$ (DEG) | YAW $\psi$ (DEG) | RUDDER ANGLE $\delta$ (DEG) | RUDDER RATE $\dot{\delta}$ (DEG/SEC) | MEAN YAW/SWAY RESISTANCE $a\ vr$ (lb) | MEAN RUDDER RESISTANCE $\delta^2$ (lb) | MEAN SWAY2 RESISTANCE $\eta_v{}^2$ (lb) | MEAN TOTAL RESISTANCE $\overline{\Delta X}$ (lb) | $\lambda\ x^2$ (lb) | MEAN APPROX ADDED RESISTANCE $\overline{J}$ (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Simple Lag Modeling Hydraulics Ts = 3.0 | | | | | | | | | | | | | |
| 60 | 0.909 | 0.229 | 1.550 | 5.498 | 1.554 | 1.321 | 0.273 | -6115.2 | -599.6 | | -747[illegible] | - 344[illegible] | - [illegible] |
| Servo-actuator Only-Proportional with Saturation | | | | | | | | | | | | | |
| 60 | 0.909 | 0.229 | 1.550 | 5.498 | 1.554 | 1.321 | 0.272 | -6114.2 | -599.1 | | -[illegible].4 | - 344[illegible] | - [illegible] |
| Servo-actuator and Rotary Power Unit - Proportional with Saturation | | | | | | | | | | | | | |
| 60 | 0.930 | 0.224 | 1.493 | 5.349 | 3.500 | 0.444 | 0.096 | -5862.4 | - 68.3 | | - 6[illegible]49.[illegible] | -1[illegible] | -1[illegible] |
| Rotary Power Unit-Hysteresis Servo-actuator Proportional with Saturation | | | | | | | | | | | | | |
| 60 | 0.927 | 0.224 | 1.491 | 5.342 | 3.536 | 0.427 | 0.080 | -5621.0 | - 63.2 | | - 6675.1 | -1[illegible] | -1[illegible] |

Table 13. Simulation Results - Controller Parameters $\begin{bmatrix} 0.3188 \\ 44.92 \\ 7.-66 \end{bmatrix}$
Beaufort 8 Sea State - 32 Knots -
Optimal Controller - Vary Rotary Power Unit

| ENCOUNTER ANGLE (DEG) $\beta$ | SWAY RATE $v$ (FT/SEC) | YAW RATE $r$ (DEG/SEC) | ROLL RATE $p$ (DEG/SEC) | ROLL $\phi$ (DEG) | YAW $\psi$ (DEG) | RUDDER ANGLE $\delta$ (DEG) | RUDDER RATE $\dot{\delta}$ (DEG/SEC) | MEAN YAW/SWAY RESISTANCE $a\ vr$ (lb) | MEAN RUDDER RESISTANCE $\delta^2$ (lb) | MEAN SWAY2 RESISTANCE $\eta_v{}^2$ (lb) | MEAN TOTAL RESISTANCE $\overline{\Delta x}$ (lb) | $\lambda\ \epsilon^2$ (lb) | MEAN APPROX ADDED RESISTANCE (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ = [illegible] 3° Rotary Power Unit-Propor-tional with Saturation 60 | 0.927 | 0.224 | 1.496 | 5.360 | 3.653 | 0.466 | 0.100 | -5623.6 | -7[illegible].4 | | [illegible] | [illegible] | [illegible] |
| $\beta$ = 4° Rotary Power Unit-Propor-tional with Saturation 60 | 0.929 | 0.223 | 1.494 | 5.352 | 3.697 | 0.461 | 0.07[illegible] | -5790.2 | -73.3 | | [illegible] | [illegible] | [illegible] |
| $\beta$ = [illegible]° Rotary Power Unit-Propor-tional with Saturation 60 | 0.930 | 0.222 | 1.490 | 5.339 | 3.723 | 0.444 | 0.065 | -5736.[illegible] | -68.[illegible] | | -6665.1 | [illegible] | [illegible] |

Table 13. Simulation Results - Controller Parameters $\begin{bmatrix} 0.3188 \\ 44.92 \\ 7.066 \end{bmatrix}$
Beaufort 8 Sea State - 32 Knots -
Optimal Controller - Vary Rotary Power Unit
(Cont)

| ENCOUNTER ANGLE (DEG) $\beta$ | SWAY RATE $v$ (FT/SEC) | YAW RATE $r$ (DEG/SEC) | ROLL RATE $p$ (DEG/SEC) | ROLL $\phi$ (DEG) | YAW $\psi$ (DEG) | RUDDER ANGLE $\delta$ (DEG) | RUDDER RATE $\dot{\delta}$ (DEG/SEC) | MEAN YAW/SWAY RESISTANCE $a\ vr$ (lb) | MEAN RUDDER RESISTANCE $\delta^2$ (lb) | MEAN SWAY² RESISTANCE $\eta_v v^2$ (lb) | MEAN TOTAL RESISTANCE $\overline{\Delta x}$ (lb) | $\lambda\ s^2$ (lb) | MEAN APPROX ADDED RESISTANCE $\bar{J}$ (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\delta_1 = $ [illegible]° $\delta_2 = 1°$ Rotary Power Unit-Hysteresis 60 | 0.930 | 0.223 | 1.495 | 5.357 | 3.739 | 0.468 | 0.092 | -5644.7 | -2[illegible].4 | | -6736.5 | [illegible] | [illegible] |
| $\delta_1 = 0.0$ $\delta_2 = 1°$ Rotary Power Unit-Hysteresis 60 | 0.923 | 0.224 | 1.493 | 5.342 | 3.246 | 0.490 | 0.095 | -5769.[illegible] | [illegible] | | [illegible] | [illegible] | [illegible] |

Table 14. Simulation Results - Beaufort 8 Sea State - 32 Knots - Discrete Controller - Optimal Controller Simple Lag for Ship Hydraulics $T_s$ = 3.0

| ENCOUNTER ANGLE (DEG) $\beta$ | SWAY RATE $v$ (FT/SEC) | YAW RATE $r$ (DEG/SEC) | ROLL RATE $p$ (DEG/SEC) | ROLL $\phi$ (DEG) | YAW $\psi$ (DEG) | RUDDER ANGLE $\delta$ (DEG) | RUDDER RATE $\dot{\delta}$ (DEG/SEC) | MEAN YAW/SWAY RESISTANCE $a\ vr$ (lb) | MEAN RUDDER RESISTANCE $\delta^2$ (lb) | MEAN SWAY² RESISTANCE $\eta_v{}^2$ (lb) | MEAN TOTAL RESISTANCE $\Delta x$ (lb) | $\lambda\ x^2$ (lb) | MEAN APPROX ADDED RESISTANCE $\bar{J}$ (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 | 0.436 | 0.126 | 0.137 | 1.541 | 1.906 | 2.623 | [illegible] | - 412.3 | [illegible] | | [illegible] | [illegible] | [illegible] |
| 60 | 0.906 | 0.230 | 1.546 | 5.489 | 1.546 | 1.337 | 0.269 | - 6121.8 | - 614.1 | | [illegible] | [illegible] | [illegible] |
| 90 | 2.354 | 0.076 | 1.730 | 2.978 | 0.166 | 0.716 | 0.398 | +11667.2 | [illegible] | | [illegible] | [illegible] | [illegible] |
| 120 | 0.677 | 0.312 | 0.275 | 0.298 | 0.363 | [illegible] | 0.051 | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] |

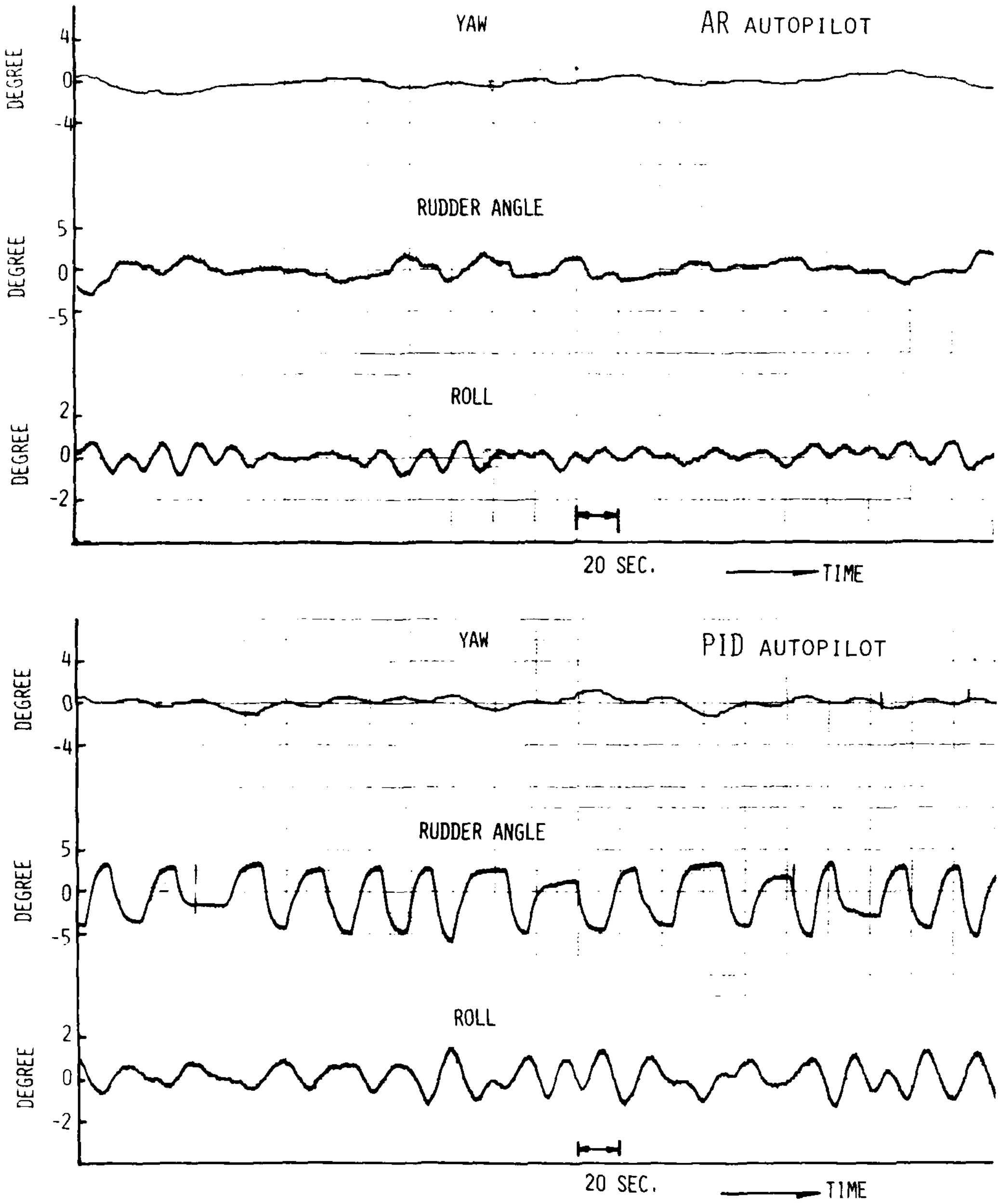


Figure 4. Typicals of the Analog Records of the AR and the PID Autopilots

Table 2. An Example of the AR Coefficients a(m), b(m)

| m | a(m) | b(m) |
|---|---|---|
| 1 | 1.0718 | 0.1542 |
| 2 | 0.1192 | 0.0989 |
| 3 | -0.3344 | -0.1545 |
| 4 | 0.0850 | -0.1443 |
| 5 | 0.3163 | 0.0144 |
| 6 | 0.0296 | 0.0282 |
| 7 | 0.2958 | -0.5028 |

Basing on the fitted model, we designed the optimal controller gains G and H under various weighting matrices Q, R and T, by the program OPTDES. At that time, we adopted 60 sec. as the optimization interval I in the evaluation function (2-2). Table 3 shows an example of the optimal gains G and H when the weighting matrices Q, R and T in (2-2) are selected as Q=25, R=1 and T=1, respectively.

Table 3. An Example of the Optimal Gain G and H

$$G^T = \begin{pmatrix} 5.101 \\ 5.130 \\ 5.156 \\ 5.174 \\ 5.171 \\ 5.147 \\ 5.104 \end{pmatrix} \qquad H = 0.366$$

4.2. On-line Controlling by the AR Autopilot

August in 1977, we carried out the full scale sea test by our AR autopilot at the Tokyo Bay. The sea state was in the Sea Moderate. The control signal was given at every one sec.. After switching from the PID autopilot to the AR one, the AR autopilot was in the transient state for 10 or 15 sec.. Then the AR autopilot steering became stationary and it continued to steered the ship stably.

In order to compare with the PID autopilot system, as soon as ending the running by the AR autopilot for about 600 sec., we continued to record the one by the PID autopilot for the same length. Fortunately, through all tests, the AR autopilot operated normally and stably.

4.3. Discussion and Comparison

Figure 4 shows the typicals of the analog records of the Yawing, the Rudder motion and the Rolling by both autopilot steerings. In the figure, it is particularly impressive that not only the Yawing but also the rolling in the steering of the AR autopilot are reduced. We think that it is because the rudder motion is less and more infrequent than the PID autopilot steerings.

Figure 5 also demonstrates the effect of the AR autopilot by the spectra of the Yawing and the Rudder motion comparing with the case by the PID autopilot. Note that the test by the PID autopilot was carried out for the same length just after the one by the AR autopilot.

dynamics, we used the programs MALCOR and FPEC, in which the former calculates the multi-variate covariance function and the latter estimates the appropriate autoregressive type model by the minimum AIC procedure. To obtain the optimal gains G and H, we used the program OPTDES. These programs are the revised versions of the programs given in the time series analysis and control program package TIMSAC (See Akaike (5)).

Figure 3 illustrate the procedure for obtaining the optimal gain. In the figure, the program OPTSIM implements a digital simulation by pseudo white noise for checking the performance of the control gains G and H which were determined by the program OPTDES. The simulation is carried out by the following formula

$$\begin{cases} Z(n) = AZ(n-1) + B\delta(n) + W(n) \\ \delta(n) = GZ(n) + H\delta(n-1) \end{cases}$$

where W(n) is the realization of the pseudo white noise. We searched the appropriate gains G and H by the repeated use of the programs OPTDES and OPTSIM. A reasonable method to determine these optimal control gains was described in details in Ohtsu et. al (10).

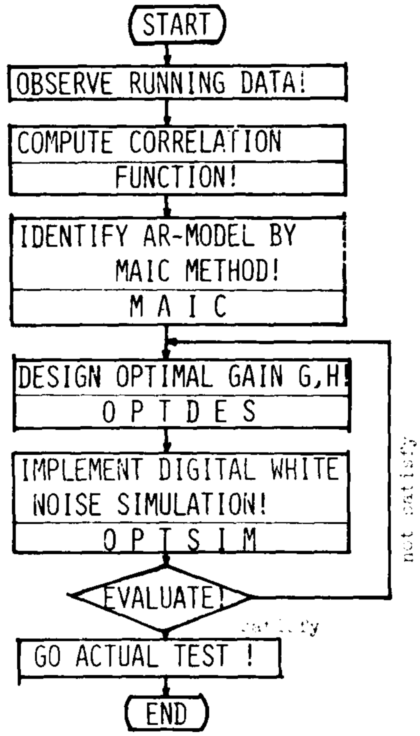

Figure 3. A Procedure to Design AR Controller

## 4. ACTUAL SEA TEST

### 4.1. The purpose and Experimental Plan of the On-line Controlling

The main purpose of the following on-line control were to test whether our theoretical expectation to realize the AR controller would be correct. Therefore, in this experiment we did not investigate the **sensitivity** of the controller to the weighting matrices Q, R, T, and so on.

At first, the TS. SHIOJI MARU was steered by a helmsman so as to include noise as much as possible. Such "unskilful steering" was necessary to obtain the data free from the feedback control. The sea state was in the Sea Moderate. We obtained 1000 observations of the yaw and rudder motion sampled at every 1 sec..

Table 2 shows the coefficients of an autoregressive type model

$$\psi(n) = \sum_{m=1}^{M} a(m)\psi(n-m) + \sum_{m=1}^{M} b(m)\delta(n-m) + \varepsilon(n)$$

fitted by the program FPEC.

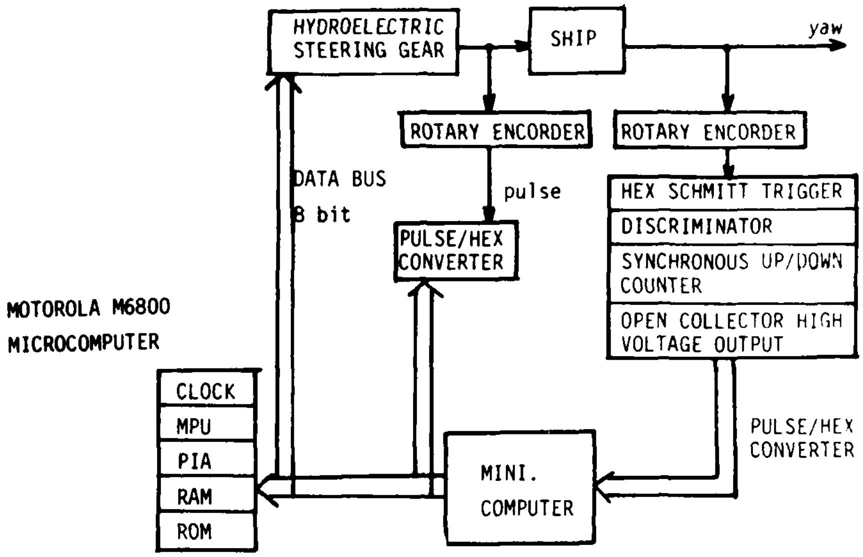


Figure 1. Blockdiagram of the AR autopilot.

## 3.3. Software for the AR controller

It is necessary to develop a real time control program to implement the optimal control law

$$\delta(n) = GZ(n-1) + H\delta(n-1) \tag{3-1}$$

in the digital computer. As we can know from (2-10), we can immediately obtain the state vector Z(n), when the new signal of yaw motion $\psi(n)$ has been obtained. Thus we can order very quickly the rudder signal to be steered. Figure 2 shows the flow chart of the steering algorithm written by an Assembly language. In the figure, the parts after ordering the rudder angle contributes to provides Z(n+1) in the form to be used in the future computation.

Besides these programs for on-line controlling, we had to prepare some programs for the identification of the ship and for designing the optimal controller. To identify the ship's

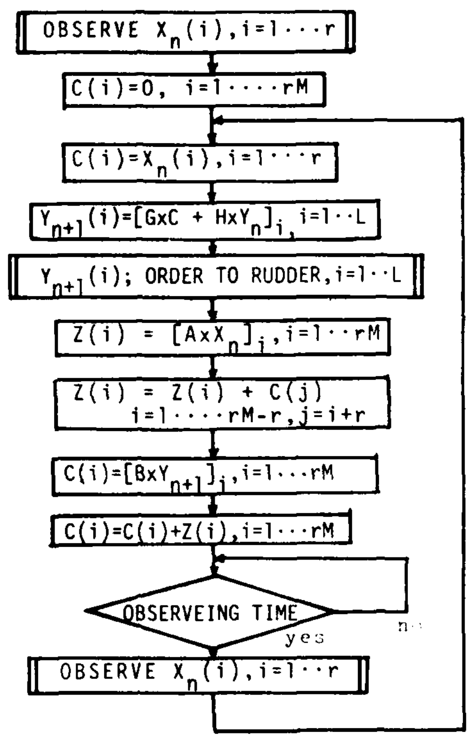


Figure 2. AR Steering Algorithm

The most interesting result found in the simulation was that the longitudinal motion such as the pitching motion was not reduced, but the transverse motion, such as the rolling, was suppressed. Considering the effect to heeling due to the rudder motion, this result is a very natural sort of thing.

### Hybrid Simulations

However, the experiment which made us believed that the AR controller possesses the excellent course keeping ability were the analog digital hybrid simulations (see Ohtsu et. al (11)). In the hybrid simulations, the digital computer controlled the ship's yawing motion simulated by an analog one. Consequently speaking, it becomes clear that the AR autopilot demonstrated not only their excellent course keeping ability through smaller rudder motion than the conventional PID type autopilot but also the robustness as the controller to various environments.

## 4.2. Hardware for the AR Controller

The digital simulation study discussed in the preceding section was clearly telling us the possibility of realizing a new AR autopilot system. Based on these considerations, we proceeded to the actual sea test using a full scale ship.

The ship used at the test was the TS. SHIOJI MARU (with about 330 gross tons.) of the Tokyo University of Mercantile Marine. The principal dimensions are shown in Table 1. It has been known that the ship

Table 1. Principal Dimensions of TS. SHIOJI MARU

| | |
|---|---|
| LENGTH | 41.70 m |
| BREADTH | 8.00 m |
| TONNAGE | 311.37 G/T |
| MAX.SPEED | 11.49 K't |
| BLOCK COEFF. $C_b$ | 0.555 |

had some unstable character around the rudder angle zero. She is furnished with the PLATH type autopilot system and the hydroelectric type steering gear driven by the Hele-Show type pump. Hereafter, we will call this conventional autopilot as a "PID autopilot."

Our DDC system is constructed with a mini-computer and a micro processor utilizing the emergency circuit of her autopilot system. The ship's heading angle is observed from a pulse/16-bit converter via a rotary encorder which is mechanically connected with the gyro-repeater and sent to the mini-computer. Then the mini-computer calculates the optimal steering angle and orders to the steering gear system via the micro processor. On the other hand, as shown in Figure 1, the actual rudder angle is observed from the movement of the rack bar of the steering gear. And the micro processor is used to control the difference between the orderd and actual rudder angles.

with

$$A = \begin{bmatrix} a(1) & 1 & & \\ a(2) & & 1 & \\ \vdots & & & \ddots \\ & & & 1 \\ a(M) & & & 0 \end{bmatrix} \quad B = \begin{bmatrix} b(1) \\ b(2) \\ \vdots \\ b(M) \end{bmatrix} \quad W(n) = \begin{bmatrix} \varepsilon(n) \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

$$C' = [1,0,\ldots,0] \tag{2-9}$$

$$Z(n) = [z_1(n),\ldots,z_M(n)]^T$$

where the element $z_i(n)$ of the state vector $Z(n)$ is defined by

$$z_1(n) = \psi(n)$$

$$z_i(n) = \sum_{j=1}^{M-i} \left\{ a(i+j)\psi(n-j) + b(i+j)\delta(n-j) \right\} \quad (i=2,\ldots,M) \tag{2-10}$$

This representation has a significant merit that the prediction value of $\psi(n+1)$ at time n is immediately obtained by

$$\hat{\psi}(n+1) = a(1)\psi(n) + z_2(n) \tag{2-11}$$

with only a little computation. It should be noted that $z_i(n+1)$, $(i=2,\ldots,M)$ is the i-steps ahead predictor of $\psi(n)$ at time n.

## 3. AN IMPLEMENTATION OF THE OPTIMAL CONTROLLER

In the former section, we have described the theoretical background of our approach to develop an entirely new optimal controller of a ship . In this section, we will describe the way how we implemented the optimal controller to an actual ship and performed an on-line sea test of the new autopilot system. Hereafter, we will call this new autopilot an *AR autopilot*. We began at first with the feasibility study by the digital and hybrid simulations.

### 3.1. Preliminary Experiment

Digital Simulations

The digital simulations were carried out as follows. (See Ohtsu et. al (8), (10).) An AR model was fitted to the running data sampled from an actual container ship at every one second. The ship's system represented by the AR model was driven by the pseudo white noise and steered by the AR controller introduced in the preceding section.

Summing up the particularly attractive characters of our AR controller, we would be able to say that

(1) The AR controller exhibited the excellent course keeping ability in spite of its smaller rudder motion than the case of the conventional autopilot.

(2) Besides the yawing, other ship's motion, in particular, the roll-motion was suppressed due to infrequent rudder motion

is achieved at the cost of increasing unreliability of the estimated parameters. On the other hand, if too low order a model is used, then the reliability of the estimated parameters are expected to increase although the power of expression of the model decreases. The best approximating model is the one which achieves the most satisfactory compromise. Akaike (3) proposes an information criterion (AIC)

$$\text{AIC} = (-2)\log_e(\text{maximum likelihood}) + 2(\text{number of parameters}) \quad (2\text{-}5)$$

for the selection of the best approximation orders. The first term of AIC measures the goodness of fit to the data and the second term the unreliability of the model. Thus by selecting the order which attains the minimum of AIC, we can obtain the most reasonable model from the statistical point of view.

## 2.2. State Space Representation

The derivation of a state space representation of the autoregressive type model (2-4) is straightforward but not unique. A seemingly natural representaion is

$$\begin{aligned} Z(n) &= A\, Z(n-1) + B\, \delta(n-1) + W(n) \\ \psi(n) &= C\, Z(n) \end{aligned} \quad (2\text{-}6)$$

where

$$Z(n) = [\psi(n),\ldots,\psi(n-M+1),\delta(n),\ldots,\delta(n-M+1)]^T$$

$$A = \begin{bmatrix} a(1) & \cdots & a(M) & b(1) & \cdots & b(L) \\ 1 & & & & & \\ & \ddots & & & & \\ & & 1 \quad 0 & & & \\ & & 0 & 0 & & \\ & & & 1 & & \\ & & & & \ddots & \\ & & & & 1 & 0 \end{bmatrix} \quad (2\text{-}7)$$

$$B = [0,\ldots,0,1,0,\ldots,0]^T$$

$$C = [1,0,\ldots\ldots,0]$$

$$W(n) = [\varepsilon(n),0,\ldots,0]^T$$

But a more expedient expression is

$$\begin{aligned} Z(n) &= A\, Z(n-1) + B\, \delta(n-1) + W(n) \\ \psi(n) &= C\, Z(n) \end{aligned} \quad (2\text{-}8)$$

## 2. THEORETICAL BACKGROUND

If an appropriate state space representation of a ship's steering dynamics is obtained, we can immediately proceed to design an optimal controller of the ship. Assume that we have a state space representation

$$
\begin{aligned}
Z(n) &= A\,Z(n-1) + B\,\delta(n-1) + W(n), \\
\psi(n) &= C\,Z(n),
\end{aligned}
\tag{2-1}
$$

where $Z(n)$ is the state vector at time $n\Delta t$, $\delta(n)$ is the rudder angle, $W(n)$ is a disturbance to the system and $\psi(n)$ is the heading angle of the ship. Then the optimal steering law subject to the criterion

$$
J[I] = E\left[\sum_{n=1}^{I}\left\{Z(n)^T Q\,Z(n) + \delta(n-1)^T R\,\delta(n-1) + d(n-1)^T T\,d(n-1)\right\}\right],
\tag{2-2}
$$

where E denotes expectation and $d(n)=\delta(n)-\delta(n-1)$, is given by

$$
\delta(n) = G\,Z(n) + H\,\delta(n-1).
\tag{2-3}
$$

The gain matrices G and H are obtained by using technique of Dynamic Programming (see Ohtsu et. al (8)).

Thus the most important problem in designing the optimal steering system is to obtain an appropriate state space representation of a ship's steering dynamics. Hereafter, we will briefly discuss this problem.

### 2.1. Identification of a ship's Steering Dynamics

We consider the ship's course keeping motion as a realization of a stationary Gaussian stochastic process. Then the identification of the ship's steering dynamics becomes the problem of the modelling of the bi-variate (heading angle and rudder angle) time series.

In this paper, we will use an autoregressive type model

$$
\psi(n) = \sum_{m=1}^{M} a(m)\psi(n-m) + \sum_{m=1}^{L} b(m)\delta(n-m) + \varepsilon(n),
\tag{2-4}
$$

where M and L are the orders of the model and $\varepsilon(n)$ is the Gaussian white noise, and refer to Akaike(5) and Kitagawa(6) for more sophisticated autoregressive moving average (AR-MA) model. The regression coefficients $a(m)$ $(m=1,\ldots,M)$ and $b(m)$ $(m=1,\ldots,L)$ are easily obtained by solving the well known Yule-Walker equation or by the method of least squares, given orders M and L (See Akaike (1),(2)). Thus the key to the success to the identification of the ship's dynamics is the determination of the suitable orders of the model (2-4). If too high order a model is used, then it may be expected that the ability of approximating the ship's dynamics tends to increase while this increase

# AN ADVANCED SHIP'S AUTOPILOT SYSTEM BY A STOCHASTIC MODEL

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ABSTRACT

An approach to the optimal controlling of ship's course keeping motion and its actual on-line sea test are described. A ship's steering dynamics is identified by an autoregressive (AR) model applying the minimum AIC procedure. Using the identified model, an optimal controller (AR autopilot) is designed. The AR autopilot is implemented to a full scale ship by using a mini-computer and a micro-processor. A successful results of the test at sea is reported and compared with the conventional autopilot system.

## 1. INTRODUCTION

Almost two decades has passed since the modern control theory moved into the limelight. However, it seemed that it has not so contributed to the practical control problems. The modern control theory requires a precise description of the system dynamics by a mathematical model. It reduces the range of application to practical control ploblems, since it has been very difficult to obtain an appropriate model of a system with the exceptional case such as the space air craft.

In time series analysis, Akaike(1), (2) developed a practical procedure for the fitting of the multi-variate stationary models. By using the procedure, we can easily obtain an appropriate model of a ship in course keeping motion. The derivation of a state space representation is quite straightforward. Thus now we got a way to success in controlling the ship's course keeping motion. The same method was used for the control of a cement rotary kiln (1[illegible]) and a boiler plant of a generating station (1[illegible]).

In this paper, we will show our attempt to develop an entirely new stochastic autopilot system of a ship. In section 2, we give a brief description of the theoretical background of our approach, and in section 3 we show how an optimal controller was implemented to an actual ship. In section 4, a successful results of an experiment of a direct digital controlling of a full scale ship are reported and the final section is devoted to further discussion and conclusion.

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of controller outlined in this paper, will result in substantial improvement in steering performance in terms of both controllability and propulsion efficiency across-the-board.

The SL-7, however, represents a particular type of a particular class of ships. It is a large, high-speed container vessel - a liner. As such it exhibits characteristics which make the vessel's dynamic behavior different from other vessels. And it represents as stringent a requirement for its analytical treatment as any directionally stable hull form.

It is reasonable to assume, from the work done to date, that most findings of this paper have general applicability to a large range of normal ship types. It is not possible, however, to make inferences, of a general nature, concerning all ships on several important issues from the results and findings of the SL-7. Specifically the findings as to the effect of steering gear nonlinearities on system performance may not be extended to directionally unstable ships, as may not the particular control system effects in following and quartering seas.

- Conditions significantly less than Beaufort 8 (Beaufort 5, for example) result in negligible penalty in terms of added resistance due to steering and negligible heading error with a properly designed steering control system for the SL-7. Depending upon the statistics of weather conditions, in terms of Beaufort Number and sea directions, encountered by a ship operating on a given trade route, the need for a controller which minimizes propulsion losses may, or may not, be established

- The advantage of the use of a controller which is adaptive to seaway direction is limited, for the SL-7. The study results show the adaptivity to seaway direction is advantageous primarily in heavy following to quartering seas at high speeds

- A higher bandwidth controller, contrary to previous belief, is required to minimize added resistance in following to quartering seas

- The principal contribution to added resistance in following to quartering seas is due to yaw/sway drag of inertial origin. The counteraction of the rudder to yaw/sway brought about by the use of a higher bandwidth controller can greatly reduce this effect, and, at the same time, reduce the yaw deviations of the ship

- The results of this work have possible implications relating to design or operational specifications for ships' autopilots. In the light of the findings of this report, the question must be asked: is "specified heading deviation with minimum rudder activity" a valid requirement for autopilots?

- The use of a two-loop steering system limits the performance possible in following/quartering seas, since root mean square rudder angle is significantly reduced compared to that of the equivalent single-loop system

- There exists no potential for limit cycles of the ship in calm water within the range of control parameters specified for the adaptive control system

- The use of a proportional two-loop steering system rather than a "bang-bang" two-loop system offers no improvement in either heading performance or added resistance due to steering in heavy seas

There exists good confidence in the results obtained and conclusions drawn from the fairly rigorous analysis of steering characteristics and performance of the SL-7 high-speed containership which has been conducted on this program to date.

A principal goal of the program was the establishment of both a design technique and resulting form of automatic steering control sytem for minimization of added resistance due to steering which have general applicability to a wide range of merchant ships. Employment of such a design technique and implementation of the form

- The modeling of the single-loop system as a linear system with simple time constant is accurate for the controller parameters selected. This is simply to say that the main pump is not saturating with the controller parameters selected - which was a design goal

Further investigation of a proportional two-loop system was carried out by varying the range of linear operation of the Rotary Power Unit between 2/3 degree error and 8 degree error before rate saturation occurred (Table 13). No significant change in performance resulted by this variation, and it can be said that use of a proportional two-loop controller offers no advantage over a "bang-bang" two-loop controller on this particular ship.

Use of a single-loop steering system, however, as is evidenced in the performance for such a system shown in Table 14, does result in greatly improved performance in terms of both heading error and added resistance in quartering/following seas at high speed.

## CONCLUSIONS

The principal conclusions resulting from this study of the SL-7 containership as they related to steering may be stated as follows:

- A steering control system may be configured which minimizes propulsion losses due to steering and maintains bounded heading performance in very heavy seas. Such a controller is best made adaptive to both speed and sea direction if the optimum in performance is sought in terms of both propulsion losses and heading error. Only slightly inferior performance results from the use of a controller which is adaptive only to speed

- An adaptive controller which minimizes propulsion losses as ship characteristics and environmental conditions change may be designed using a self-optimalizing technique employing a performance criterion which is an approximation to true added resistance

- The design of an adaptive controller which employs such an approximate performance criterion for on-line adaptivity of controller parameters is difficult since an unconstrained search for a minimum is not possible, limiting both the adaptive techniques which may be used and also the resulting performance possible

- The use of an adaptive controller per se is clearly not a sufficient condition for propulsion losses minimization; nor is an adaptive controller a necessary condition for significant reduction in propulsion losses

- Performance approaching that obtainable by an adaptive controller may be realized from the existing Universal Gyropilot (UGP) by appropriate selection of specified internal and operator controls

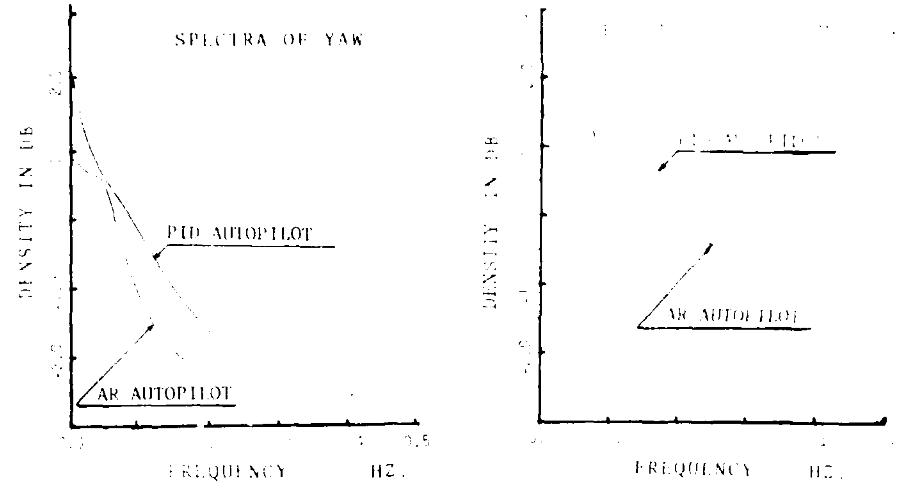


Figure 5. Spectra of Yawing and Rudder Motion.

About [illegible] observations were used to estimate these spectra.

We can clearly see the excellent ability of the AR autopilot in the course keeping quality. Moreover, we also noticed that the superior course keeping quality is realized by the rudder motion with more low power than the PID autopilot. These results are actually proving that our expectation from the various simulations was correct.

## [illegible]. CONCLUSION

We have described an theoretical approach to the ship's optimal control by an autoregressive model and the actual sea test by the AR autopilot using the model.

From these tests, we obtained the follwing conclusions:
(1) The AR autopilot has high ability to keep the desired course by the infrequent rudder motion.
(2) Due to its infrequent rudder motion, the AR autopilot can reduce not only the energy loss of the steering gear system but also the Rolling motion. It is probably because the AR model of the ship's course keeping motion obtained by the minimum AIC procedure is highly predictable to the future ship's motion.
(3) The assessement by the digital simulation is effective to determine the optimal controller gains [illegible].

However, we should continue the following studies;

(1) Confirm the robustness of the AR autopilot against the various sea states.
(2) Try to control by the multi-variate model of the course keeping motion including the Yaw-Rate and Rolling etc.
(3) Determine the optimal sampling rate of the real time control.
(4) Try to design more advanced autopilot system by using an AutoRegressive Moving Average (AR-MA) model.
(5) Try an ADC (Analog Digital Coordinate) control system backing up the conventional autopilot system by the AR one.

Furthermore, we may expect to apply this model to the control of a fin stabilizer, a semi-submerged ship, ship's boiler and diesel engine.

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# DESIGN PROCEDURES FOR A SURFACE SHIP STEERING CONTROL SYSTEM

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## INTRODUCTION

This papei describes the basic procedures used to produce a discrete control algorithm from a set of general system requirements for steering control of a standard surface ship. The design procedure used was one that we all believe in but seldom have the opportunity to exercise. First, the design requirements were laid out in the greatest possible detail. Since the automatic steering system was to be embedded in a much larger system, and since the control design was not started until after considerable time had been spent formalizing system concepts, we were fortunate enough to be able to obtain a definitive set of requirements at the onset of our work. This is in distinct contrast to many other design procedures which begin with a general requirement for a "good system" and continue with the system designers formulating the specific design requirements. (Is it any wonder that the design meets the requirements more often than not?) The second step was the formulation of a set of assumptions or conditions under which the system would be expected to work. This is often a point of contention between the system designers and system users who, of course, want the steering system to work under all conditions, including obviously impossible conditions such as the loss of both rudders. The final step was the development of detailed technical procedures and formulations ensuring that each of the requirements was met. This final step actually consisted of concept formulation and concept evaluation via simulation (full scale trials would also be valuable). The concept formulation and evaluation steps are often repeated several times, hopefully with each cycle getting successively shorter. This particular design has been through just one cycle. That is, we have produced a set of equations for a control system which we feel meets the design requirements and which is currently undergoing real-time system simulation evaluation. We will present some of the results in this paper. Whether or not another design cycle is required depends upon a complete analysis of these results, but present indications are that only minor modifications will be required.

## DESIGN REQUIREMENTS

As mentioned above, the formulation of the design requirements should be the first step in the design cycle and is certainly the most important one. It is essential that both the control system designer and his customer have a solid agreement on the exact nature of what will be developed and delivered. If this is not done, many months of effort can be wasted, causing considerable disagreement between the designer and his customer. Since one of the goals of this paper is to present a particular design procedure in both a technical and a historical format, we will be quite formal about establishing the design requirements and assumptions.

The design requirements are often thought of as arising from the customer and placing constraints on the designer, while the system assumptions are thought of as arising from the designer and placing constraints on the customer. This is seldom, if ever, the case. Usually both the requirements and the assumptions are the result of negotiations between both parties involved. For this particular design, we were jointly able to enumerate the following basic system requirements:

- The system shall be capable of both coursekeeping and course changing.
- The system shall be capable of operating in both an automatic mode in which the system has control over the rudder, and in an aided mode in which "quickened" information pertaining to desired rudder commands is displayed to the helmsman.
- During the aided mode, the helmsman will be presented with two displays; one consisting of the quickened rudder display superimposed on the actual helm position, the other consisting of a discrete display indicating whether the helmsman is following the quickened rudder display with sufficient accuracy and, if not, the direction in which he should turn the wheel. The system shall contain the logic for generating both displays.
- The system shall be capable of following both a continuously varying ordered course and an ordered course that will change only upon receipt of a discrete signal.
- The system shall have two response modes to changes in the ordered course; a normal mode and a fast response mode.
- The system shall always respond to a change in ordered course with a minimum angular turn.
- The system shall be as adaptive to its environment (e.g., sea state, speed) as is practical and shall require no operator adjustment of system parameters.
- The system shall respond as rapidly as possible to changes in ordered course. Control shall be as near to "bang-bang" as is practical and shall use full rudder authority when possible.
- The operator will have the option of setting the required turn diameter. The system shall not generate a rudder command in excess of the angle required to establish this steady state turn diameter.
- The control system equations shall be delivered in discrete format with all differential equations transformed into suitable difference equations and shall include all necessary logic for operation on a digital computer.
- The system sampling rate shall be no greater than 10 times per second.
- The system shall require no more than 4000 16-bit words for implementation.

As can be seen, the requirements run the gamut of technical subjects from control system design through human factors and software design. This, however, represents the usual assemblage of requirements for modern systems with more and more emphasis being placed on digital control and man/machine interactions. A final, nontechnical requirement placed on the system design by the customer was that the entire design procedure be adaptable to a broad range of classes of surface ships and be delivered along with the final design.

ASSUMPTIONS

As with requirements, it is essential that both the system designer and the customer have an agreement on what the former calls "assumptions" and the latter calls "limitations." Many of these assumptions are so basic that the designer does not feel the need to call special attention to them; his intuitive feeling is that everyone realizes these assumptions will be made. This, however, is not always the case, and only when the system is delivered does the designer discover that the customer did not also make these assumptions. We will list only a few of the assumptions that were made for this design as examples; the others dealt mainly with software/hardware implementation details and would contribute little to this presentation. The basic assumptions are as follows:

- The system will have control over the rudder(s) only.
- If the ship has multiple rudders, they will be coupled and move as one.
- The system will be required to function properly only for ahead speeds above some steerage way minimum. No reverse operation will be required.
- The system will not be required to evaluate the accuracy or validity of its input data. Data will be used as received.
- The system will only be required to maintain an ordered heading, it will not have to perform path following.

CONTROLLER FORM

Based on experience gained in the previous design of several similar systems, we have determined that a suitable form for a course-keeping controller is that shown in Figure 1, a block diagram of the closed loop system. The form of the filters and controller could be "derived" using optimal control and estimation theory as was done originally, but can be equally explained using a classical approach. The notch filter is required to remove high frequency components of heading due to first order wave effects. The motions due to these effects have frequencies well above closed loop frequencies and attempts to correct them would result in useless oscillations of the rudder. Therefore, a double-pole, low pass filter is used to remove any high frequency components of input that are not at the fundamental wave frequency. The controller itself is what is commonly called a PID (proportional plus integral plus derivative) controller. Estimation of additional states, such as lateral velocity, is not essential for stabilization, and the added complexity would not be worth the marginal performance improvements. Thus, as far as compensation and stabilization are concerned, it is only necessary to select:

- the form of the notch filter,
- a time constant for the low pass filter, and
- three gains.

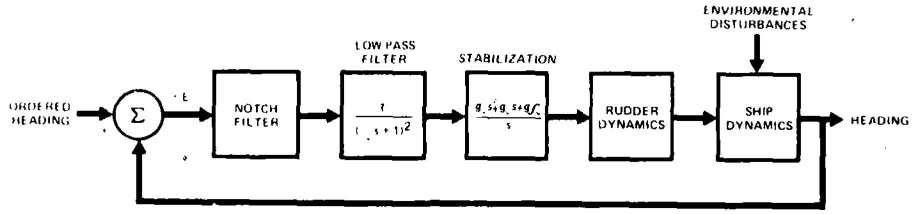


Figure 1. Closed Loop Control System

## PROCEDURES

### Stabilization

Techniques for stabilizing ship steering systems are legion and most have serious drawbacks that are not at first realized by the control system designer. The most serious drawback is that the control system of a surface ship is basically non-linear. Nearly every designer realizes that ship motion equations may be non-linear, but this particular non-linearity is not vitally important since the control system can overcome it and can even mitigate the control problem related to unstable ships. The most important non-linearity is the rudder rate limit. Since rate limited systems cause large phase shifts when the rate limit is exceeded for a substantial portion of any operating period, such systems should be designed so that rate saturation seldom, if ever, occurs. This problem is compounded by the fact that rudder systems typically have small maximum rates, in the order of 3 to 4 degrees per second. Of course, keeping rudder rate limits small is desirable from the viewpoint of hydraulic power consumption, but this is seldom considered important for surface ships.

For a fixed forward speed, control in the horizontal plane can be completely described using only three states: heading, heading rate, and lateral velocity. For simplicity, an ordered heading of 0 degrees is assumed, thus the heading and heading error will be the same and will be used interchangeably in this paper. The interaction of the roll equation with these states, while important for simulation purposes, is considered to be negligible from the viewpoint of control system design. Since the lateral velocity state is exceedingly difficult to measure, coursekeeping stabilization systems usually consist of gains on heading error and heading error rate only. We thereby eliminated the optimal control approach to our problem since it would have forced us to use gains on the three systems states. While it is possible to apply non-linear optimization techniques to minimize a quadratic cost functional (as is done in optimal control applications) with constraints on the resulting gains, the complexity would not have been justified in this simple case. Pole placement techniques

would also have been applicable, but suffer from the serious drawback that we would have needed to know, a priori, where we would have liked to have the closed loop poles.

Because of these difficulties, we developed an approach to the design of course stabilization systems that, while admittedly heuristic in its first stages, allowed us to rapidly determine a stabilizing set of gains while avoiding the problems of rudder rate limiting. This approach has been used in the design of course stabilization systems for both surface ships and large submersibles, and has been amply demonstrated by results of simulation, model tests, and full scale trials. The procedure can be simply stated as follows:

1) Use the heading equation alone to find an approximate relationship between the heading rate gain and the heading gain.

2) Use this relationship and the rudder rate limit constraint to determine the approximate heading and heading rate gains.

3) Use these gains, linear models of the ship and the rudder dynamic systems, and additional filtering as required to remove seaway disturbances (discussed later) to perform a linear analysis, including Bode plots, Nyquist diagrams, etc. Adjust the heading rate gain until adequate stability margins are realized.

4) Perform time domain simulations using all the non-linearities of the ship and the rudder system to evaluate the final design.

We have found the linear analysis technique to be such a good approach for steering stabilization that adjustments to the controller gains have not been required after the final step for any ship with which we have worked.

This procedure will be demonstrated first symbolically and then with a numerical example. The basic equation for ship heading may be written as

$$I_z \dot{r} = \frac{\rho}{2} L^5 N_{\dot{r}} \dot{r} + \frac{\rho}{2} L^4 N_r u\, r + \frac{\rho}{2} L^3 N_{\delta r} u^2 \delta r \qquad (1)$$

where: $\frac{\rho}{2}$ is one-half the density of water ($\cong 1$ for sea water in the English system)
$I_z$ is rotational inertia about the vertical axis through the center of gravity
$N_{\dot{r}}$, $N_r$, $N_{\delta r}$ are ship coefficients
u is the ship's axial velocity (ft/sec)
r is the ship's heading rate (deg/sec)
$\delta r$ is the rudder angle (deg)

If we desire the rudder angle to be a linear function of the heading and heading rate, we may write, with a slight abuse of notation,

$$\delta r = g_\psi \psi + g_{\dot{\psi}} \psi \qquad (2)$$

$$r = \dot{\psi} \qquad (3)$$

so that equation (1) becomes

$$\ddot{\psi} - \frac{(L^4 N_r u + L^3 N_{\delta r} u^2 g_{\dot{\psi}})}{(I_z - L^5 N_{\dot{r}})}\dot{\psi} - \frac{L^3 N_{\delta r} u^2 g_{\psi}}{(I_z - L^5 N_{\dot{r}})}\psi = 0 \tag{4}$$

Equation (1) can be written as

$$\tau_R \dot{r} + r = \frac{N_{\delta r} u \, \delta r}{L \, N_r} \tag{5}$$

where the open loop time constant of the heading equation is

$$\tau_R = -\left(\frac{I_z - L^5 N_{\dot{r}}}{L^4 N_r u}\right) \tag{6}$$

We may look upon this 'natural' time constant as a lower limit not to be exceeded, that is, the design goal should be to have a system with time constants of the order $\tau_R$. This design goal can be interpreted as desiring that Eq. 4 have two poles at $1/\tau_R$. That is, equation (4) should be of the form

$$\ddot{\psi} + \frac{2}{\tau_R}\dot{\psi} + \frac{1}{(\tau_R)^2}\psi = 0 \tag{7}$$

Matching terms between equations (4) and (7) yields the following relationships for the heading and heading rate gains:

$$g_{\psi} = -\frac{L^5 N_r^{\,2}}{N_{\delta r}(I_z - L^5 N_{\dot{r}})} \tag{8}$$

$$g_{\dot{\psi}} = \frac{L \, N_r}{N_{\delta r} u} \tag{9}$$

One of the goals of this demonstration is to provide an approximate relationship for $g_{\dot{\psi}}$ in terms of $g_{\psi}$. This is easily derived from equations (8) and (9) as

$$g_{\dot{\psi}} = -\frac{(I_z - L^5 N_{\dot{r}})}{L^4 N_r u} g_{\psi} \tag{10}$$

Experience has shown that this is only an order of magnitude relationship and that the gain on heading rate may have to be several times larger than indicated by equation (10). Fortunately, however, the ensuing calculations are not very sensitive to changes in this relationship.

Now that we have obtained an approximate expression for the ratio of heading rate gain to heading gain, we can proceed to the next step which is to compute the actual gains such that the rudder is not rate saturated during normal operation. In order to do this we formulate the following problem.

Given the control law

$$\delta = g_{\dot{x}}\dot{x} + g_x x \tag{11}$$

find the maximum gains, $g_{\dot{x}}$, $g_x$, such that

$$|\dot{\delta}| \leq C \tag{12}$$

for $x = A \sin \omega t$ (13)

After some manipulation, equation (12) becomes

$$\omega g_x A \, (1 + \omega^2\alpha^2)^{\frac{1}{2}} \leq C \tag{14}$$

where $\alpha = g_{\dot{x}} / g_x$

If we now assume that the frequency of oscillation about which we are concerned is the closed loop natural frequency (since oscillations at seaway frequencies will be removed by filtering to be discussed later), then this frequency is a function of the ship's coefficients and the gain on heading. From equation (4) this is seen to be

$$\omega_N = (K g_\psi)^{\frac{1}{2}} \tag{15}$$

$$\text{where } K = \frac{L^3 N_{\delta r} u^2}{(I_z - L^5 N_{\dot{r}})} \tag{16}$$

From equations (14) - (16) a relationship for the heading gain in terms of the rudder rate limit and the expected magnitude of oscillation is obtained as

$$g_\psi{}^3 \, (K + K^2\alpha^2 g_\psi) \leq (C/A)^2 \tag{17}$$

where

$\alpha$ is $g_{\dot\psi}/g_\psi$

K is a compound of ship coefficients ($Kg_\psi = \omega_N{}^2$)

C is the rudder rate limit

A is the magnitude of oscillation through which no rate limiting is desired.

As indicated earlier, the ratio of heading rate gain to heading gain implied by (10) usually is too low; however, the computation of the heading gain from (17) is not very sensitive to the choice of $\alpha$. The procedure is straightforward from this point except for the choice of the variable A. This variable must be selected so that "reasonable" excursions in heading do not cause rate saturation of the rudder, especially for small changes in ordered heading. Values of A may be selected in the range of $5^\circ$ to $20^\circ$, depending on how "tight" a control system is desired. The smaller the value of A, the larger the gain. Once the gain on heading is computed from (17) the gain on heading rate is computed from (10). The open loop Bode plot for the controller plus ship plus rudder dynamics is used to determine closed loop stability via assessment of gain and phase margins. Phase margins should be adjusted so that the smallest value across the speed range is approximately $70^\circ$; this adjustment is made by varying the gain on heading rate.

As a specific numerical example, a design for a fairly large destroyer class will be demonstrated. For this class we have a rudder rate of 3 deg/sec and have picked the amplitude limit for linear response, A, to be $15^\circ$. Substituting for actual ship coefficients, equation (17) becomes

$$g_\psi{}^3\ (1 + .0805g_\psi) = 17497.8/u^2 \tag{18}$$

from which it is easy to compute an approximate expression for the gains on heading and heading rate in terms of the forward speed in knots as

$$g_\psi = .5306 + 18.144/V_k \tag{19}$$

$$g_{\dot\psi} = \frac{29.47}{V_k} + \frac{1007.6}{V_k{}^2} \tag{20}$$

Realizing that equations (19) and (20) are only coarse approximations to the final gains, we will abandon them temporarily, select the other system parameters, and then return to the gains for adjustment in the final analysis step.

As mentioned above, low pass filtering is introduced to remove high frequency noise that might occur for any of several reasons, including wave noise not sufficiently attenuated by the yet-to-be-

designed notch filters. This time constant should be selected as high as possible consistent with maintenance of adequate stability margins. Another way of stating this constraint is, "Do not let the phase shift associated with the low pass filtering exceed some specified value at the crossover frequency." (The crossover frequency, $\omega_c$, is the frequency at which the open loop Bode plot has a magnitude of unity with a positive phase margin.) For any reasonably stable system with response approximately like a second order system, the crossover frequency does not exceed the natural frequency, that is,

$$\omega_c \leq \omega_N \tag{21}$$

Therefore, if the maximum allowable phase shift at crossover is designated as $\phi_{mx}$, then

$$2 \tan^{-1}(\tau_\psi \omega_N) \leq \phi_{mx} \tag{22}$$

Using the standard approximation for the tangent at small angles, this becomes

$$\tau_\psi \leq \frac{\phi_{mx}}{(2\omega_N)\ (57.3)} \tag{23}$$

Experience with this type of system has taught us that this type of filtering is worth a good deal of phase margin, therefore we selected a maximum phase shift of 30 degrees resulting in

$$\tau_\psi = .262/\omega_N \tag{24}$$

Since the natural frequency is a function of already determined parameters (we will not be adjusting the heading error gain), we can immediately compute the following approximate curve fit (c.f. equations (15) and (16) )

$$\tau_\psi = .664 + 26.86/V_k \tag{25}$$

Gain on Integral Error

The choice of an integral gain term is not critical as long as it is small enough not to affect closed loop ship stability. Since ships spend a great deal of time in conditions that generate relatively constant bias forces, speed of convergence of the integral term is not an important factor, and five or ten minutes for convergence is not too much. We have arbitrarily decided that the integral gain should be such that an error of $\psi_{EI}$ will generate a rudder angle of $\delta_I$ if held for N periods of length $T = 2\pi/\omega_N$. This relationship can be expressed as

$$(g_{\int\psi}\psi_{EI})\ N\ T = \delta_I \tag{26}$$

yielding the following expression for the integral gain

$$g_{\int\psi} = \frac{\omega_N \delta_I}{2\pi N \psi_{EI}} \tag{27}$$

Selecting the values

$$\delta_I = 1,\ \psi_{EI} = 1,\ N = 5$$

we get the following expression for the integral gain

$$g_{\int\psi} = .0318\ \omega_N \tag{28}$$

or

$$g_{\int\psi} = .001154 + .0001333\ V_k \tag{29}$$

Seaway Adaptive Filtering

Since the ship will be subject to wave induced forces and moments that will be at too high a frequency to be effectively countered by the closed loop control system, the effects of these high frequency components must be attenuated by appropriate filtering. If these high frequency components are not filtered, not only will excessive rudder motion occur with increased power consumption and increased system wear, but also the possibility of instability due to commanding rudder rates greater than the maximum available will be very likely. Wave frequency spectra may often be characterized by a single-peaked curve. While multi-peaked spectra do occur, there is usually a dominant peak whose effects must be removed. The standard manner in which narrow band noise is removed from a signal, and the one that is frequently used in ship control design, is to introduce a notch filter "tuned" to the requisite frequency. We have selected the simplest form of a notch filter which may be written using Laplace notation as

$$G(s) = \frac{s^2 + \omega^2}{s^2 + 2\zeta\omega\ s + \omega^2} \tag{30}$$

This filter may be "derived" from optimal estimation theory by assuming that a white noise signal is corrupted with additive narrow band noise. The resulting steady state Kalman filter has the simple, second order transfer function shown above. The only remaining problem is the se-

lection of the notch frequency, $\omega$. This must be selected as a function of ship's forward speed and the actual sea state. However, we would like not to require an operator input for this selection but rather have it an automatic procedure. The only constraint imposed on the adaption technique is that it must not allow the notch frequency to become so low that significant degradation of stability results. Essentially, we utilize two parallel notch filters, one tuned to a lower frequency to preserve stability, and one tuned sufficiently high so as to include all frequencies of interest. The upper and lower notch frequencies are scheduled as a function of ship's forward speed. A linear combination of the two filters is formed with a proportionality variable selected by a computational algorithm that minimizes the total output noise. We have investigated several computational techniques and finally settled on one that chooses the proportionality variable, which ranges from zero to unity, based on the percentage of time that the average output level of one filter exceeds that of the other. The actual procedure that we used is rather complex and the details would contribute little to this presentation. Suffice it to say that it has been demonstrated to be highly efficacious during actual sea trials and that convergence times of 15 to 30 seconds are common. This means that even local variations in encounter frequencies are compensated for.

Linear Stability Analysis

The preceding paragraphs have described a general approach to obtaining the parameters necessary for stabilizing a surface ship heading control system. It was admitted freely at many points in the procedure that certain approximations were used whose validity must be verified once all the design information is at hand. In order to check the validity of the assumptions we have made with regard to their ability to generate a stable system, we have selected the gain and phase margins of the resulting open loop system to be the variables of primary interest. A rule of thumb valid for many systems is, "if the response resembles that of a second order system, the damping ratio is approximately .01 times the phase margin." Therefore, to minimize overshoot and provide the necessary robustness for dealing with uncertainties in the environment, we desire a phase margin of approximately 70° or more across the entire speed range. Figure 2 shows phase margin for the design as established thus far, including the lowest possible notch filter frequency at each speed. This shows that our first approximation controller parameters were very good indeed. However, since we desire phase margins slightly higher than those indicated, we also show the phase margins with the gain on heading rate adjusted. We have selected a rate gain three times higher than that computed by equation (20) for good stability. Final adjustments to these parameters can then be made as the result of simulation or full scale trials.

We wish to emphasize again that stabilization is essentially a trivial matter and can be achieved by many techniques, including trial and error. The critical factor is not mere stabilization, but a realization that the major destabilizing non-linearity of the system is likely to be the rudder rate limit which must be avoided.

**Design of Aiding System**

One of the requirements of the system design is that it provide operator aiding during manual control operation. This was to consist of two displays; the desired rudder angle as computed by the automatic

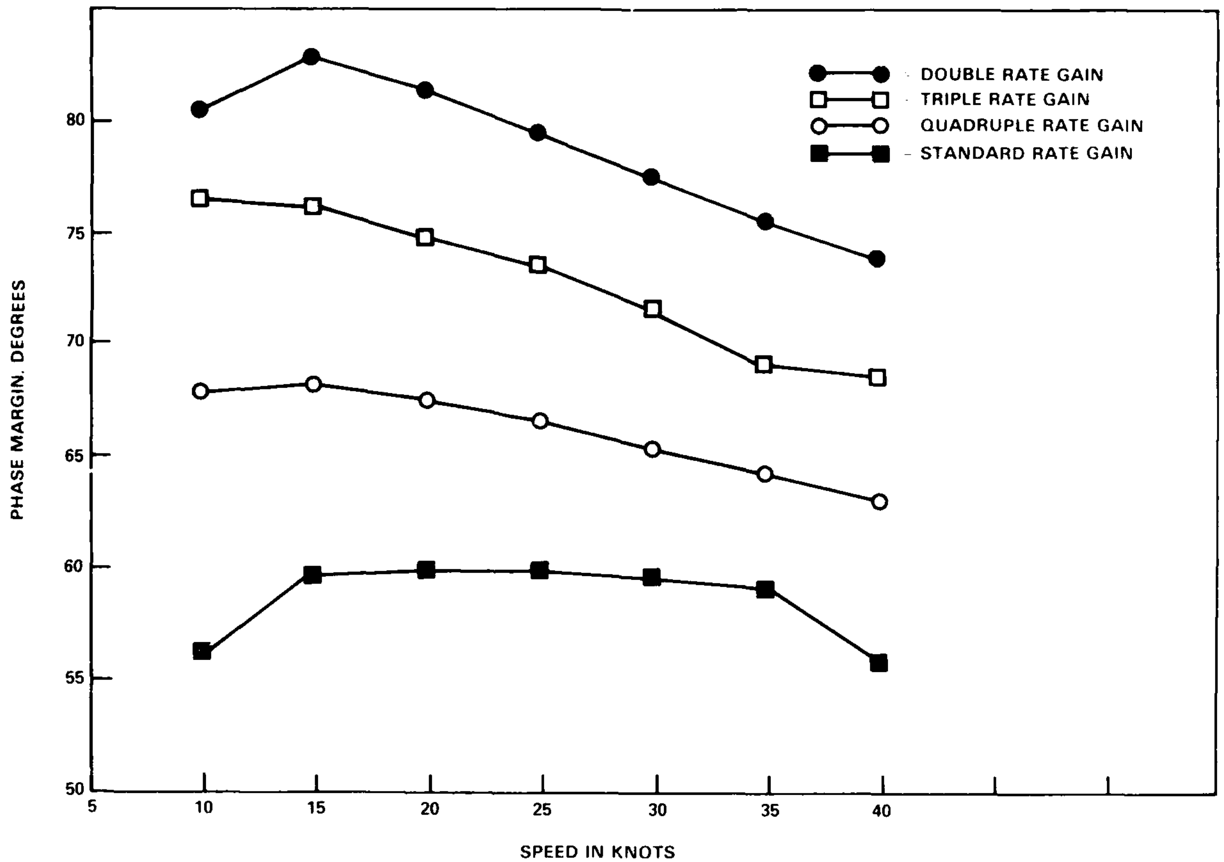


Figure 2. Phase Margins with Rate Gain Adjustment

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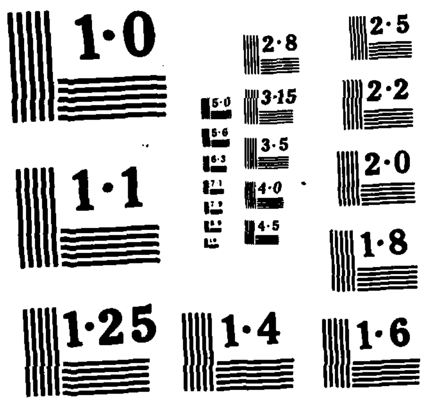
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system superimposed on the actual helm angle, and a three-light display telling the operator whether his following accuracy is sufficient or whether he should turn his helm to port or starboard. If we assume that the operator will respond fairly quickly to the helm indicator light and that his response will be to move the helm to approximately the position indicated by the automatic system, then the closed loop system will respond as if there was a deadzone in the rudder response. We could analyze the closed loop system using a describing function technique to insure that the resulting oscillations be sufficiently small, but the process would be quite complex. We have selected an alternative procedure which has proven accurate for fairly low frequency systems and which is somewhat conservative. We make the following assumptions:

1) The "deadzone" will cause a limit cycle and that cycle will be larger than the one that would be caused by positioning hysteresis, etc.

2) The limit cycle thus caused will not result in reaching the 2nd quantization level.

3) The limit cycle will be at ship closed loop frequencies.

Let $A_{mx}$ be the maximum allowable error. The limit cycle is then

$$\psi_E = A_{mx} \sin \omega t \tag{31}$$

Since the rudder angle is a function of the heading and heading rate as follows

$$\delta r = g_\psi \psi + g_{\dot\psi} \dot\psi \tag{32}$$

the rudder angle resulting from this oscillation will (neglecting rudder dynamics) be approximately

$$\delta r = A_{mx} \left( g_\psi{}^2 + (g_{\dot\psi} \omega_N)^2 \right)^{\frac{1}{2}} \sin (\omega t + \phi) \tag{33}$$

Using the relationships of equations (10) and (15) and the adjustment on the rate gain, equation (33) becomes

$$\delta r_{mx} = A_{mx} g_\psi \; (1 + .75 \; g_\psi)^{\frac{1}{2}} \tag{34}$$

However, it may be that assumption (3) is not valid and that the limit cycle will be of very much lower frequency, essentially due to an open loop integration that generates heading while the rudder command is in the deadzone. In this case, a conservative estimate of the allowable error in the difference between desired and actual helm angles reduces to

$$\delta r_{mx} = A_{mx} g_\psi \tag{35}$$

We have elected to use equation (35) due to its simplicity and conservatism and we have selected $A_{mx}$ to be $1^{\circ}$. This choice guarantees that the oscillations in heading due to the aided mode form of operation will not exceed $\pm 1^{\circ}$ in calm seas as long as the helmsman is reasonably alert. The final relationship is also intuitively appealing in that much more accurate rudder control is required at high speeds than at low speeds as one might expect.

Rapid Response Requirement

The rapid response requirement generated the ancilliary requirement for bang-bang control for course changing based on the well known fact that time optimal response in control limited situations leads to full-on control. In linear, second order systems with position-limited control, it is possible to generate a so-called "switching curve" that is a function of the position and rate of the controlled variable. This curve is such that any combinations of the controlled variables on one side of the curve requires full positive control while full negative control is required on the other side of the curve. Phase space trajectories start from the initial conditions and continue until they intersect the switching curve at which time the control is reversed and the trajectory follows the switching curve until the target set, generally the origin, is reached. Unfortunately there are several drawbacks to the application of the bang-bang principle, both in the general case and in the specific ship control application. These drawbacks are:

- The order of the switching curve is the same as the order of the system. Thus a second order system has a two-variable switching curve, a third order system has a three-variable switching curve, etc. The complexity of computations required for even a third order system is great. The ship control problem is at least fourth order (including rudder dynamics) and even higher if the control system has its own internal dynamics.

- A high degree of accuracy in the description of the system to be controlled is required or the ensuing control response will cause the target set to be missed and a limit cycle response will result. Knowledge of ship dynamics is generally not that accurate since it models test data of questionable accuracy.

- There are two limits in the controller of the surface ship; position limits and rate limits of the rudder.

For these reasons, alternative techniques to bang-bang control have been suggested. One of the most common is to impose a mixed-control strategy by dividing the phase space into two regions. One region, near the origin, represents a target set within which linear control strategy is applied. It is in the remaining region that bang-bang control is applied. The major advantage of this technique is that the target set is no longer a point but a region and is therefore much less likely to be missed. Also, the limit cycle response that would likely have appeared is eliminated. However, there still exists the difficulty associated with computing the high order switching curve and there will now be a discontinuity in control when the boundary of the target region is crossed. In order to mitigate these difficulties we proposed

and tested an alternative approach. If we designate the rudder command as x, then we desire a function, f(x), that is linear within some specified region about the origin and then rapidly approaches saturation outside that region. The function must be smooth and must also have the following characteristics:

$$f(-x) = -f(x) \tag{36}$$

and

$$\frac{df(x)}{dx} > 0 \text{ for } x > 0. \tag{37}$$

A set of functions of the form

$$f_N = x(1 + c|x|^N) \quad \text{for } N = 1, 2, 3 \ldots . \tag{38}$$

almost naturally suggest themselves. If we wish no more than a deviation of $\delta$ in linearity over the range $\pm x_{mx}$, then c must be chosen such that

$$c \le \frac{\delta}{x_{mx}|x_{mx}|^N} \tag{39}$$

After some trial and error calculation, it was decided that a choice of c = .1 and N = 3 would provide satisfactory results. It is important to note that only that portion of the rudder command that is NOT due to the integral control calculation should be processed through the non-linearity. If this is not done, the regime of non-linearity might include the target set point; an undesirable state of affairs.

### Turn Diameter Scheduling

The ship under investigation in this study responds in a very linear manner to rudder inputs. Thus it was found that a rudder angle could be computed as a simple constant divided by the desired turn diameter, independent of speed. The operator of the system sets his desired turn diameter and the control system computes the rudder angle which will generate this turn diameter. This value is then imposed as a limit on the maximum amount of rudder angle used during a turn. For ships with a less linear response, curve fits of rudder angle as a function of turn diameter and ship's speed might have to be constructed, but this is not a very formidable task. The simulation results shown later are indicative of the efficacy of a simple solution to this problem.

### Miscellaneous

While the foregoing discussion of the ship control design appears to be quite detailed, many items of both practical and theoretical significance have been omitted to keep this paper within practical

dimensions. Before presenting the simulation results, we will list some of the items that were involved in the final design but not discussed, in the hopes that they may prove helpful to designers in similar situations.

- Ship's speed for parameter scheduling should be filtered to prevent possible instabilities due to local fluctuations in gain values.

- Generation of additional gains for the fast response mode can be made by appropriately adjusting A in equation (13).

- During aided mode operation an adjustment can be made to the low pass filter time constant to compensate for operator response delays which are considerable longer for low bandwidth systems than they are for aircraft.

- The choice of a continuous-to-discrete mapping should be made with some care and followed with a Z-transform analysis to insure adequacy of the mapping over the required frequency range.

- The size of the time step will seldom be determined by the results of a stability analysis such as indicated above.

  Aliasing problems may drive the choice and the control designer will want the time step to be as small as possible. However, if the time step size is too small, computer accuracy limitations may affect notch filter stability.

- Ordered heading inputs must be suitably filtered to prevent discontinuities from reaching the notch filters, otherwise an undesirable "ringing" type response will result. (Note: Heading error not heading should be the input to the notch filter to maintain desired accuracy levels from 0 to 360$^\circ$.)

- Conditions must be established to prevent the integral control segment from functioning during certain times, such as while course changing.

- Accuracy requirements for execution must be established to insure adequate performance at sea.

- Great care should be taken in setting initial conditions and default values to ensure that safe and reasonable responses always occur.

It has been our experience that handling the "miscellaneous" portion of the controller design often requires greater time and care than is associated with those portions of the design which can be addressed using theoretical or computational techniques.

## SIMULATION RESULTS

The simulation results shown below are from the first generation design described on the preceding pages without modification. As will be seen, these results demonstrate the validity of this approach. Figures 3 through 6 compare the response of the ship/control system with and without the non-linear control strategy that approximates bang-bang response. While there is really not a great deal of difference

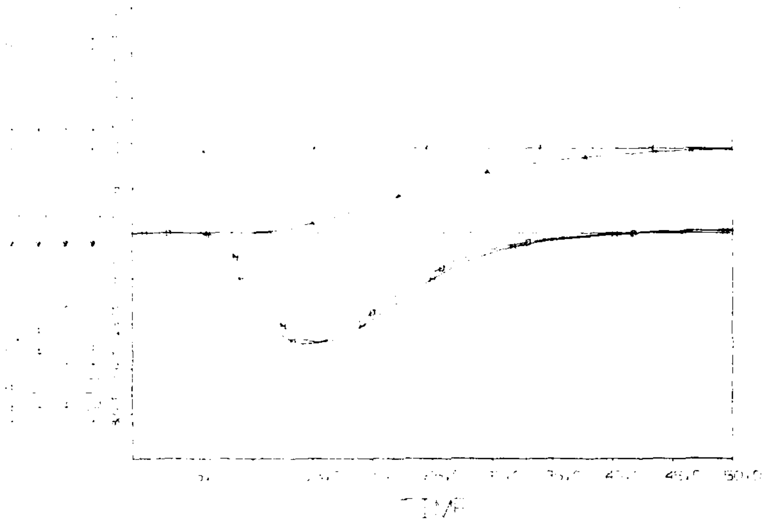

Figure 3. Response to 15° heading change with linear control at 20 knots.

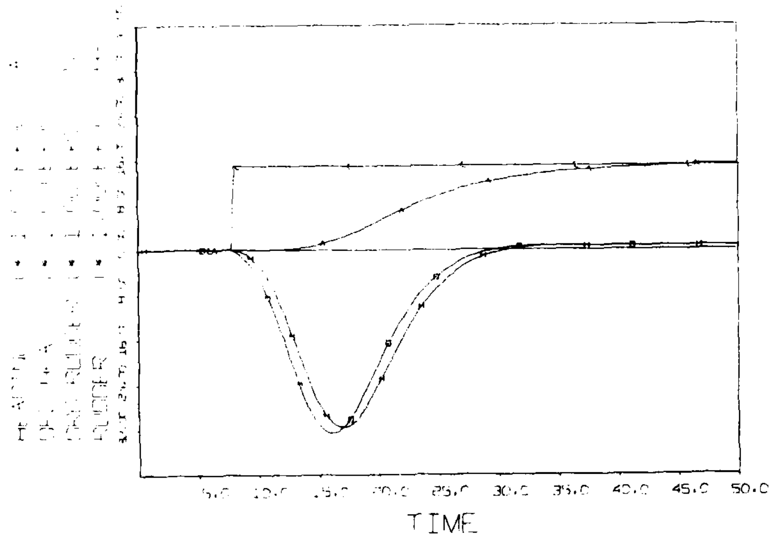


Figure 4. Response to 15° heading change with non-linear control at 20 knots.

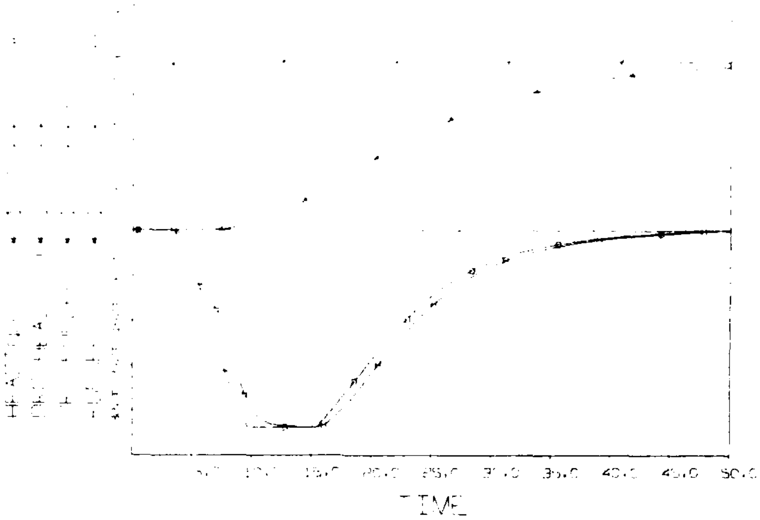


**Figure 5.** Response to 30° heading change with linear control at 20 knots.

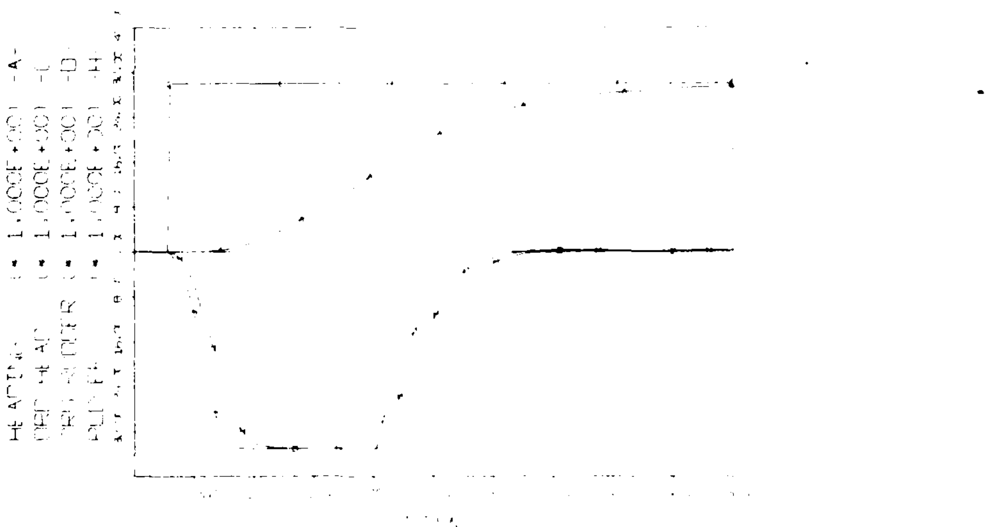

**Figure 6.** Response to 30° heading change with non-linear control at 20 knots.

between the responses of the two systems, a definite advantage is attained by using the non-linear system. For the $15^{\circ}$ course change, the ship is within $2^{\circ}$ of ordered course approximately 8 seconds sooner using the non-linear control. For the $30^{\circ}$ course change, the ship is within $5^{\circ}$ of ordered course approximately 5 seconds sooner using the non-linear control. That this difference is not greater is attributable, in part, to filtering of ordered heading which slows overall response and, in part, to the lack of tuning of the non-linear system. However, it should be kept in mind that even these modest gains in time (15 to 20%) may be important in target acquisition and/or weapons evasion.

The adequacy of the simple model for estimating turn diameter as a function of rudder angle is demonstrated in Figures 7 and 8 in which the instantaneous turn diameter is plotted as a function of time into the turn. The actual turn diameter is quite close to the ordered turn diameter at all speeds.

Figure 9 shows typical operator response during aided mode operation. The operators were asked to move their helm only when requested to do so by the aiding lights, and then to move at a fairly high rate until their helm ordered rudder angle was nearly the same as the control system ordered angle. The subsequent transient response was very much like that of the automatic system, except that during steady state operation a limit cycle resulted due to the deadzone effect discussed earlier. The amplitude of the limit cycle was within the $\pm 1^{\circ}$ limit desired, indicating the validity of the simplified analytical approach. Figure 10 shows the corresponding automatic response.

## SUMMARY

We have presented, in some detail, the procedure we have developed for stabilizing and compensating a surface ship heading control system. The unique aspects of this design procedure are:

- It inherently takes into account the major non-linearity of the system which is the rudder rate limit.
- It recognizes the need for low pass filtering to remove broadband sources of noise that always occur from the seaway and elsewhere.
- It contains on-line, adaptive filtering to remove the high magnitude, narrow-band portion of the seaway noise. This filtering is both effective and rapidly convergent.
- It allows one to rapidly and easily determine preliminary estimates of all compensation and stability parameters. From there one can proceed to a final determination using generalized analysis procedures and simulation results.

In addition, we have briefly indicated techniques for improving response capabilities and providing operator aiding signals during manual control. While analytical techniques do provide the basis of the results presented, we wish to emphasize that most often the judgment of the control system engineer is required to formulate the final system design. That is, despite the best efforts of the theoreticians over the past decade, especially with regard to optimal control, the key element remains human decision-making which is the result of an intimate association with the physical system to be controlled.

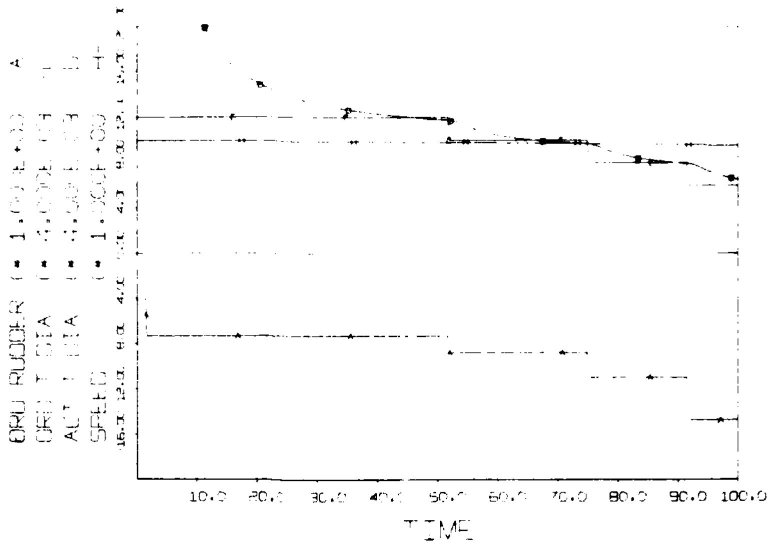


**Figure 7. Actual turn diameter as a function of ordered turn diameter at 10 knots.**

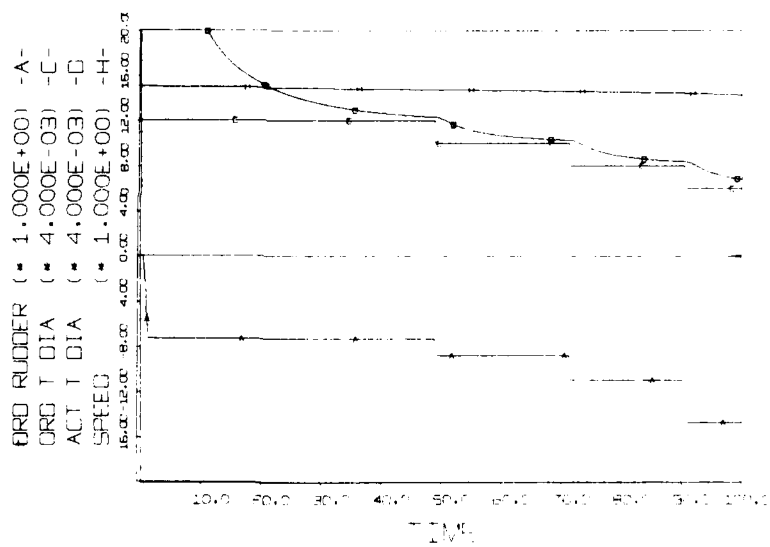


**Figure 8. Actual turn diameter as a function of ordered turn diameter at 15 knots.**

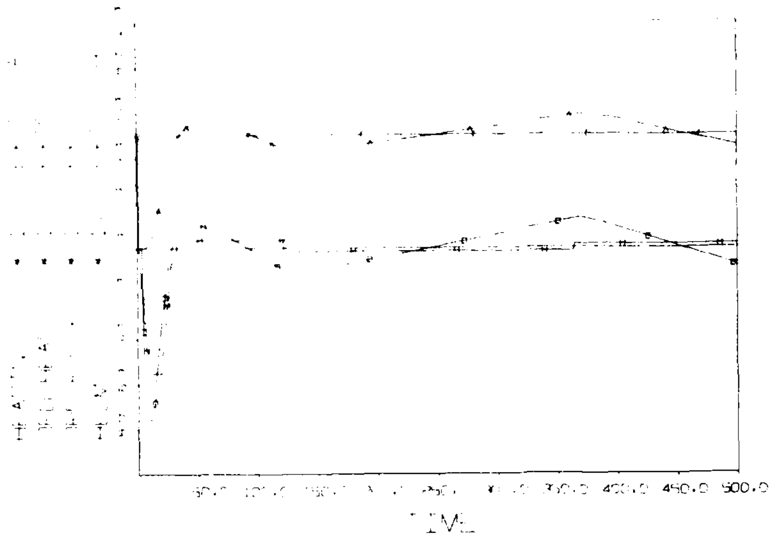


Figure 9. Manual response to $5^{\circ}$ heading change using aided mode at 20 knots.

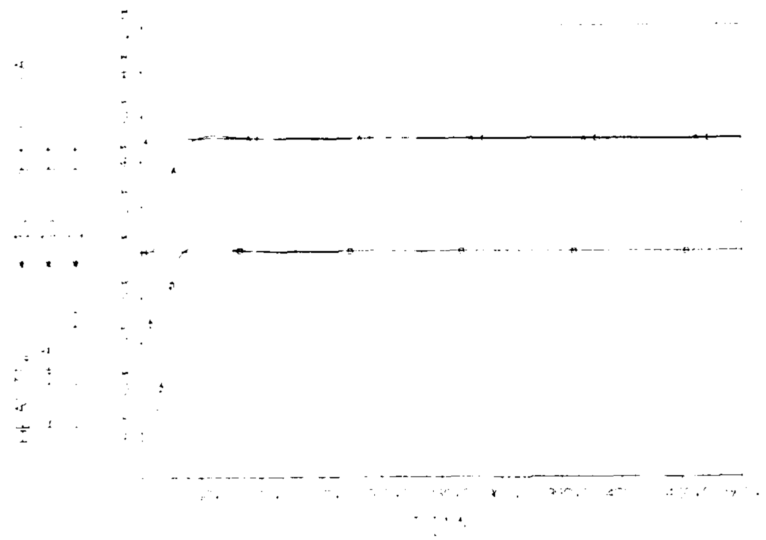

Figure 10. Response of automatic system to $5^{\circ}$ heading change at 20 knots.

Again, there were many, many aspects of the design procedure that have not been described in any detail due to space limitations. We mention this only to emphasize the point that, even for this simple surface ship system whose total design occupied approximately two months, a considerable amount of effort was spent on the details related to implementation, while very little time was spent on stabilizing and compensating parameter determination.

LIST OF SYMPOSIUM AUTHORS, SESSION CHAIRMEN,
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| Dejka, W.<br>Chairman, Session H<br>Naval Ocean Systems Center | | | |

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